THE UNIVERSITY OF ALBERTA

LOAD TESTS OF GLUED LAMINATED ARCHES

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

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DEPARTMENT OF CIVIL ENGINEERING

by

H. N. Kupczynski

under the direction of

Professor J. Longworth

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UNIVERSITY OF ALBERTA

SCHOOL OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "Load Tests on Glued Laminated Arches", submitted by H.N. Kupczynski, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Two groups of glued laminated arches were tested to destruction in a laboratory loading apparatus constructed to simulate the application of concentrated loads to an actual field structure. One group of six specimens was tested in a relatively dry condition while the other group of six specimens was subjected to severe moisture conditions for two months prior to testing. Specimens were stock sizes supplied by a local fabricator and were 1-1/2" x 4-1/2" in cross section and curved to a radius of about 18 feet. Coast region Douglas Fir material was used in the laminates which were glued together with a casein-type water-resistant glue.

In order to determine properties of the material in bending and compression a series of tests to destruction were carried out on beam and column specimens (both dry and wet).

The severe moisture conditions reduced the ultimate load capacity of the arch members by approximately 56%. The wet beam and column specimens which were tested at a lower moisture content than the arch specimens experienced corresponding reductions of 25% and 40% respectively in modulus of rupture and ultimate compression stress parallel to the grain. Contrary to common assumptions, failure stresses at the extreme fibers for the dry arch specimens were appreciably lower than either the modulus of rupture obtained in the dry beam tests or the ultimate compression stresses obtained in the dry column tests. Initial stresses in the arch specimens were not taken into account. Serious deterioration of the glue occurred in the wet arch specimens causing partial delamination in some instances. In the wet beam and column specimens deterioration of the glue had not progressed as far and there were no apparent signs of delamination.

ACKNOWLEDGMENTS

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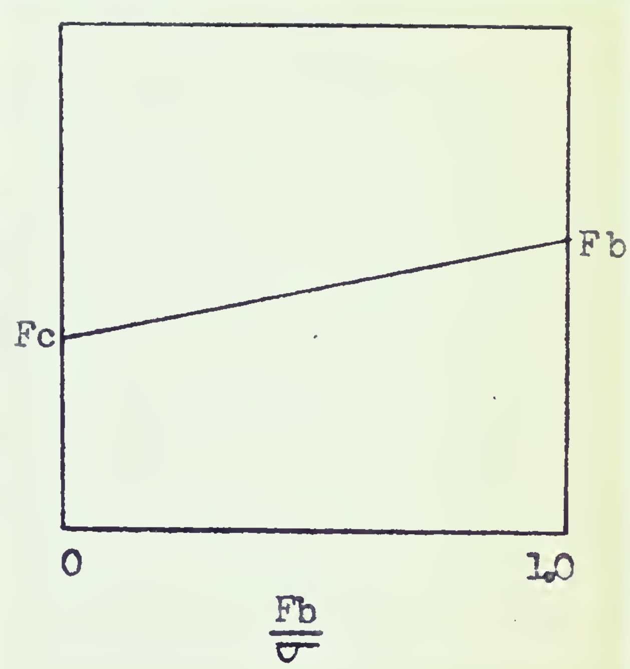
I. INTRODUCTION

With the introduction of glued laminated construction, wood, because it possesses relatively good resistance to tension, compression, and bending, is being widely used in fabrication of a great variety of sizes and shapes of structural members. It has become particularly popular in curved members such as glued laminated arches.

In a structure, arch members are subjected to combined beam and column action. For such a condition it is generally accepted that failure stresses are intermediate between the ultimate compressive strength of the wood and its modulus of rupture and that intermediate values are dependent on the ratio of the maximum bending stress to the maximum unit normal stress. For purposes of simplicity a linear variation has been assumed wherein the maximum stress variation is represented by a straight line from the ultimate compressive strength (Fc) where the ratio of maximum bending stress to maximum normal stress ($\frac{Fb}{\sigma}$) is zero to the modulus of rupture where the ratio of ($\frac{Fb}{\sigma}$) is one. According to Newlin and Trayer *(5) this relationship is actually not linear. However, a straight line relationship is a conservative assumption and because of its simplicity it is generally used in design of members for combined bending and axial load.



* See Bibliography.

In addition to the combined stress action that occurs, the effect of curvature also requires consideration in design. The National Building Code states that the allowable unit stresses in bending must be modified by a curvature factor which depends upon the ratio of laminate thickness to the radius of curvature of the laminate. This factor is an allowance for initial bending stresses produced in fabrication of the member. It is based on tests conducted by T.R.C. Wilson of the U.S. Forest Products Laboratory. The National Building Code does not require modifications due to curvature for compression stresses parallel to the grain. According to Wilson, material bent up to a curvature equal to 80 times the laminate thickness appears to suffer no significant loss in compressive strength parallel to the grain. Since members are practically never fabricated to such sharp curvatures no reductions or modifications are required in the Code for compressive stresses parallel to the grain.

A third design consideration not required in straight members is the investigation of the magnitude of radial stresses. These must not exceed allowable Code unit stresses in tension or compression perpendicular to the grain as the case may be. A theoretical expression based on the assumption that bending stress is linearly distributed throughout the section is used to compute radial stresses.

Although glued-laminated arches are being widely used, very little information regarding their structural behavior is available. This can probably be attributed to the fact that curved shapes are more difficult to test than straight members. The ideal method of testing such members would be to construct a full size structure and load it to destruction under controlled field conditions. A test of this type would provide a

true representation of a member's behavior in a field structure. However, in such a program it would be quite difficult to apply a uniform dead load to the structure. Furthermore, it would be difficult to measure deformations. It is, therefore, often desirable to test members in a laboratory under variations to field conditions. Some of the variations that may be necessary include testing of shorter lengths than are existent in the field; eliminating the effects of nailed roofing and providing some other means of lateral support; providing hinges which are not actually existent in the field at the reaction points; and loading by means of concentrated loads in place of more uniform field loading. Laboratory apparatus can be devised to test members in a horizontal plane such that measurements of deformations and strains can be taken quite simply. The information thus obtained will approximate the behavior of a member under actual field conditions.

Frequently, glued-laminated arches are used in structures such as barns and curling rinks where condensation of water vapor is a common occurrence. This condition will raise the moisture content of the member and therefore affect its strength. It may also have some deteriorating effect on the glue. T.R.C. Wilson (4) has stated that precautions should be taken against moisture condensation but he has not indicated what reduction in capacity may be expected if no precautionary measures are taken. More information on the effects of moisture on arches as well as on general arch behavior would be desirable.

The present investigation was set up to test the suitability of a laboratory testing apparatus for arches and also to investigate the relationship between failure conditions in arch specimens and beam and column specimens.

II. OBJECT AND SCOPE

The primary objects of this investigation were to observe

a) the behavior of glued laminated arches when loaded to destruction,

b) the effects of high moisture contents on the behavior of glued laminated arches.

Twelve standard arch rib sections fabricated by a local fabricator were tested. Six of these were tested in the condition in which they were received while the other six were subjected to severe moisture conditions for approximately two months before being tested.

A secondary investigation was carried out on glued laminated columns and beams of the same material to establish properties in bending and in axial compression. In each case, twelve specimens of which six were in a relatively dry state and six in a wet state were tested.

III. TEST SPECIMENS

1. Arch Specimens

The specimens tested were actual stock sections used in a 32-foot span structure. They consisted of six laminates 1-1/2" by 3/4" glued together to form a section 4-1/2" deep and 1-1/2" wide. The chord length of the specimens was approximately 23'6". All specimens were surfaced on four sides and were designated as being either "right" or "left". The "right" specimens had a radius of curvature of 18.0 feet to the inner surface while the "left" specimens had the same radius of curvature but to the outer surface of the arch. This property resulted from concentric fabrication of specimens i.e. two specimens, a "right" and "left" were fabricated side by side at the same time in the same set of pressure clamps.

Laminates were joined end to end by pre-gluing scarf joints having a slope of 1 to 12 and a hook scarf 1/8 inch high. Generally there were two to three such scarf joints in each laminate of the specimen. Laminates were glued together under a pressure of 150 pounds per square inch for 16 hours with a water-resistant casein-type of glue sold under the trade name of Monsanto No. 1911. Glue was applied at room temperature of about 60° F. at a controlled spread of 80 pounds per 1,000 square feet.

The wood used in fabrication of the specimens was a Coast region Douglas Fir D clear grade, close grained or better.

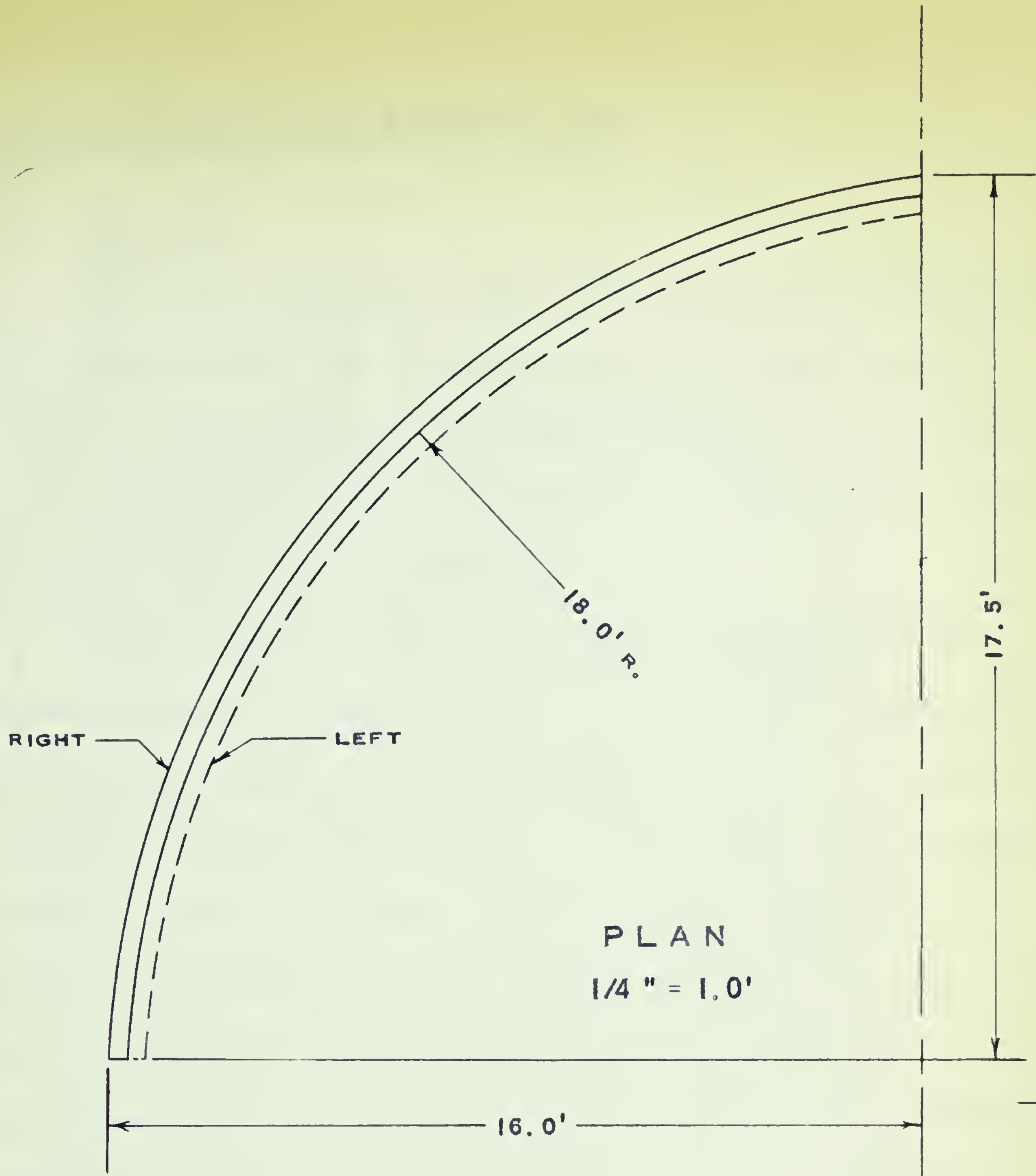
2. Beam Specimens

The beam specimens consisted of six laminates 1-1/2" by 3/4"

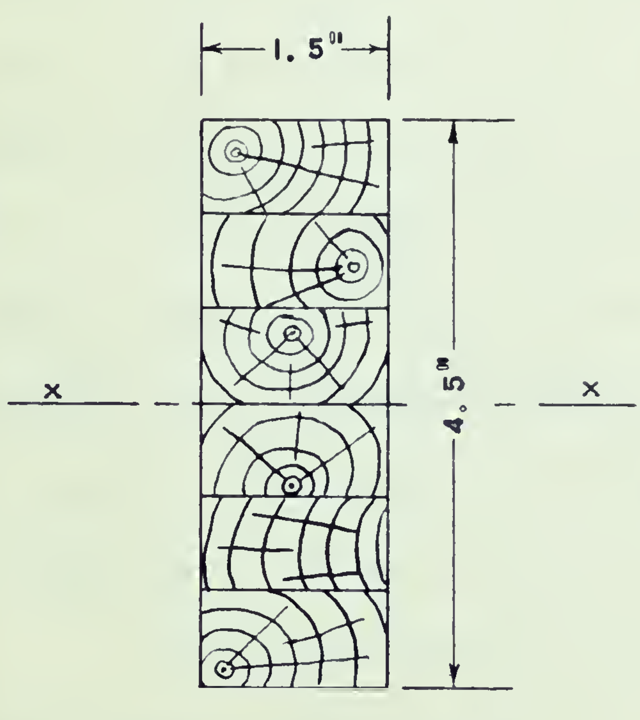
glued together to form a straight member 1-1/2" wide, 4-1/2" deep, and 12 feet long. The material and fabrication were the same as for the arch specimens.

3. Column Specimens

Since only a nine foot test span was used in the beam tests, column specimens were obtained by sawing samples 12 inches long from one of the ends of the beam specimens.



PLAN
1/4" = 1.0'



SECTIONAL VIEW
HALF SIZE

CROSS - SECTIONAL AREA - 6.75 IN.^{2}
MOMENT OF INERTIA ABOUT
THE X-X AXIS - 11.39 IN.^{4}

FIG. 1

PLAN AND SECTIONAL
VIEWS OF
SPECIMEN GLUED
LAMINATED ARCHES

IV. LOADING APPARATUS AND INSTRUMENTATION

1. Arch Tests

The loading apparatus used in the arch tests was designed to deliver a concentrated load at approximately the quarter point of a 23.72 foot test span supported by a hinge reaction at one end and a roller reaction at the other end. Figures 2, 3 and 4 show an assembly and two views of the loading apparatus.

A wide flange section (24 WF @ 76) 21 feet long with extensions attached at both ends was used as a reaction beam. At one end the extension consisted of a wide flange section (8 WF @ 31) to which the hinge reaction was attached. At the other end, two angles (6"x6"x1/2") bolted to the flange and web of the reaction beam supported an inclined welded plate shape upon which the roller travelled. The roller end represented the crown of the field structure, which, under symmetrical vertical loading would deflect in a vertical direction only. To represent this vertical direction in the tests it was necessary to incline the roller base plate such that the angle it made with the chord of the arch was the same as the angle which a vertical line made with the chord in the field condition. This angle was calculated to be $42^{\circ}\ 24\text{-}1/2'$. Making allowances for the fact that the arch chord was slightly inclined to the reaction beam to allow for greater roller travel the required angle of inclination between the base plate and the reaction beam was determined as $45^{\circ}\ 48'$.

Load was initially applied in a direction parallel to the roller support plane and 6.58 feet away from it. Two hydraulic rams acting in series and mounted between two 3/4" diameter bridle rods

connected to the flange of the reaction beam were used to apply load through a ball joint to a triangular wooden bearing block (6 inches long) attached to the arch. A series ram connection was required to provide sufficient travel (11-1/2 inches) for the anticipated deflection at the load point. Load was observed on a pressure gauge calibrated in 20-pound increments to 5,000 pounds.

Five wide flange beams (6 WF @ 20) projecting from the reaction beam were fitted with greased wood runners to provide support against lateral buckling upwards. These beams were spaced as follows (starting from the hinge end): 3.25', 2.70', 2.95', 4.35', and 6.60'. This spacing was chosen in order to clear the deflection measuring apparatus. Six rubber-castered carriers supported the arch specimen from beneath. Five of these were located at the same positions as the projecting wide flange beams while the sixth one was located near the roller end.

Strains were measured with electrical resistance SR-4 Type A-3 strain gauges which were mounted parallel to the longitudinal axis on the top and bottom laminates at four locations: quarter point (hinge end), theoretical point of maximum moment, centerline and at a point 20 inches from the load point toward the roller end. See Figure 11 for strain gauge and deflection point locations. These strain gauges were connected through a Baldwin SR-4 twenty-point switching unit to a Baldwin portable SR-4 strain indicator type L which was calibrated to give direct strain readings in micro-inches per inch to the nearest 10 micro-inches.

Ball-point pens mounted in six wooden yokes attached to the arch at its centerline axis recorded deflections on graph paper mounted on small wooden tables. Four of the yokes were located at the strain

gauge positions; the fifth at a location 20 inches away from the load point on the side opposite the strain gauge position, while the sixth was bolted to the axle of the roller. See Figures 2, 8, and 9 for views of this apparatus.

2. Beam Tests

The loading apparatus for testing beam specimens was designed to deliver concentrated loads at the third points of a nine-foot test span supported by a hinge reaction at one end and a roller reaction at the other end.

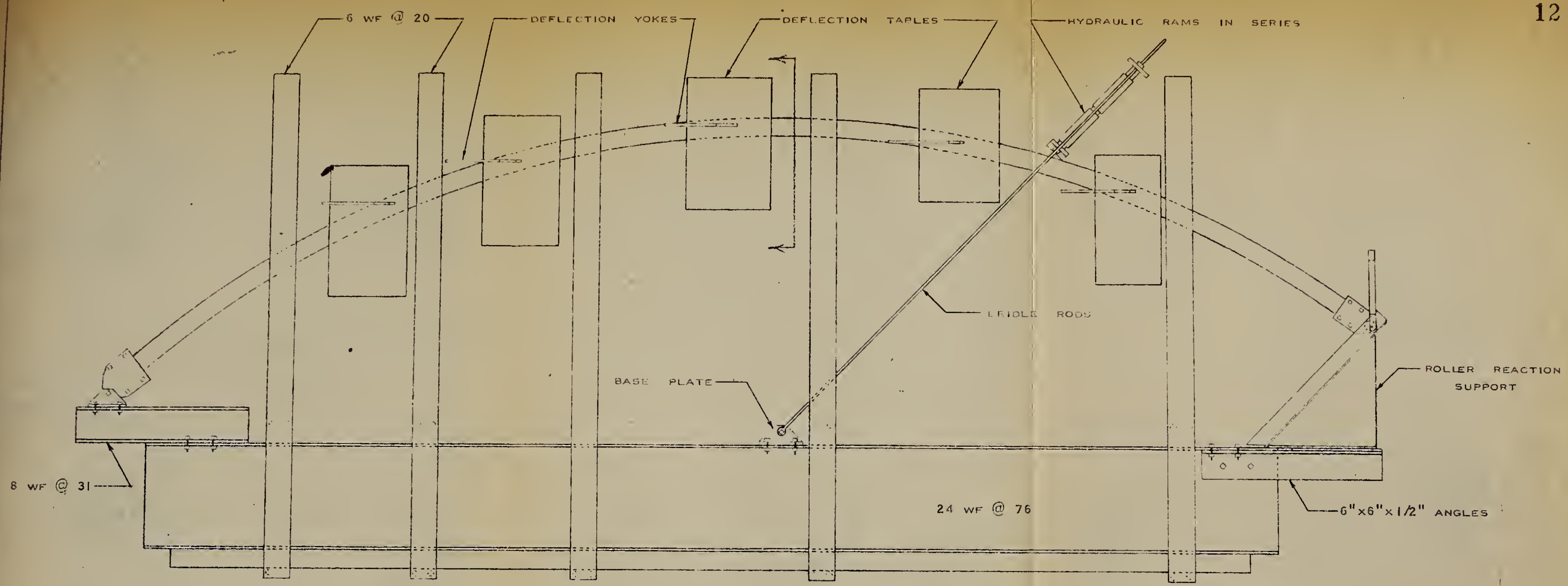
Load was applied vertically by two rams acting in series. The jacking load was transferred to a reaction beam (24 WF @ 76) through two vertical wide flange sections (6 WF @ 20) bolted to the reaction beam. See Figures 5 and 6 for views of the apparatus. A steel rail placed in an inverted position was used to transmit load from the rams to two triangular iron blocks situated at the third points of the span.

Supports consisted of a pedestal with a hinged bearing at one end and a 3-1/4 inch diameter roller at the other end.

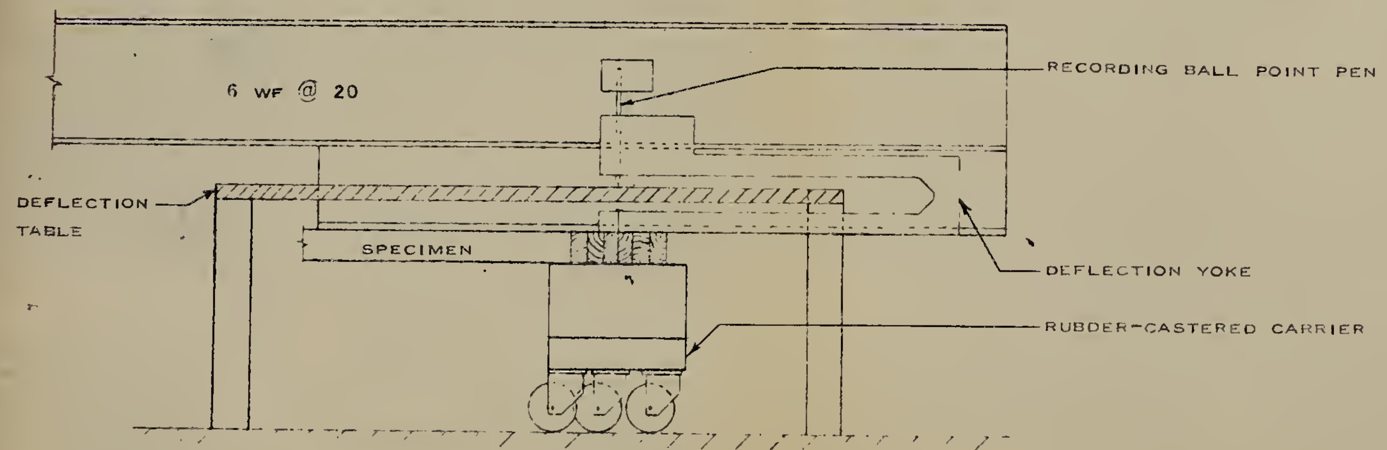
Strains were measured with the same apparatus as that used in the arch tests. Deflections at midspan were measured by taking readings with a precise surveyor's level on a steel rule graduated to 0.01 inches and attached to the side of the specimen.

3. Column Tests

Column specimens were tested axially in a universal testing machine having a capacity of 200,000 pounds. Strains were measured by means of mechanical Mercer gauges graduated in increments of 0.001 inches and electrical resistance SR-4 type A-3 strain gauges. See Figure 7 for an assembly view of the apparatus.



PLAN
1" = 1'0"



SECTIONAL VIEW
1/8 SIZE

FIG. 2

ARCH TESTING APPARATUS

SCALES - AS NOTED

MARCH 3, 1960

H. N. K.

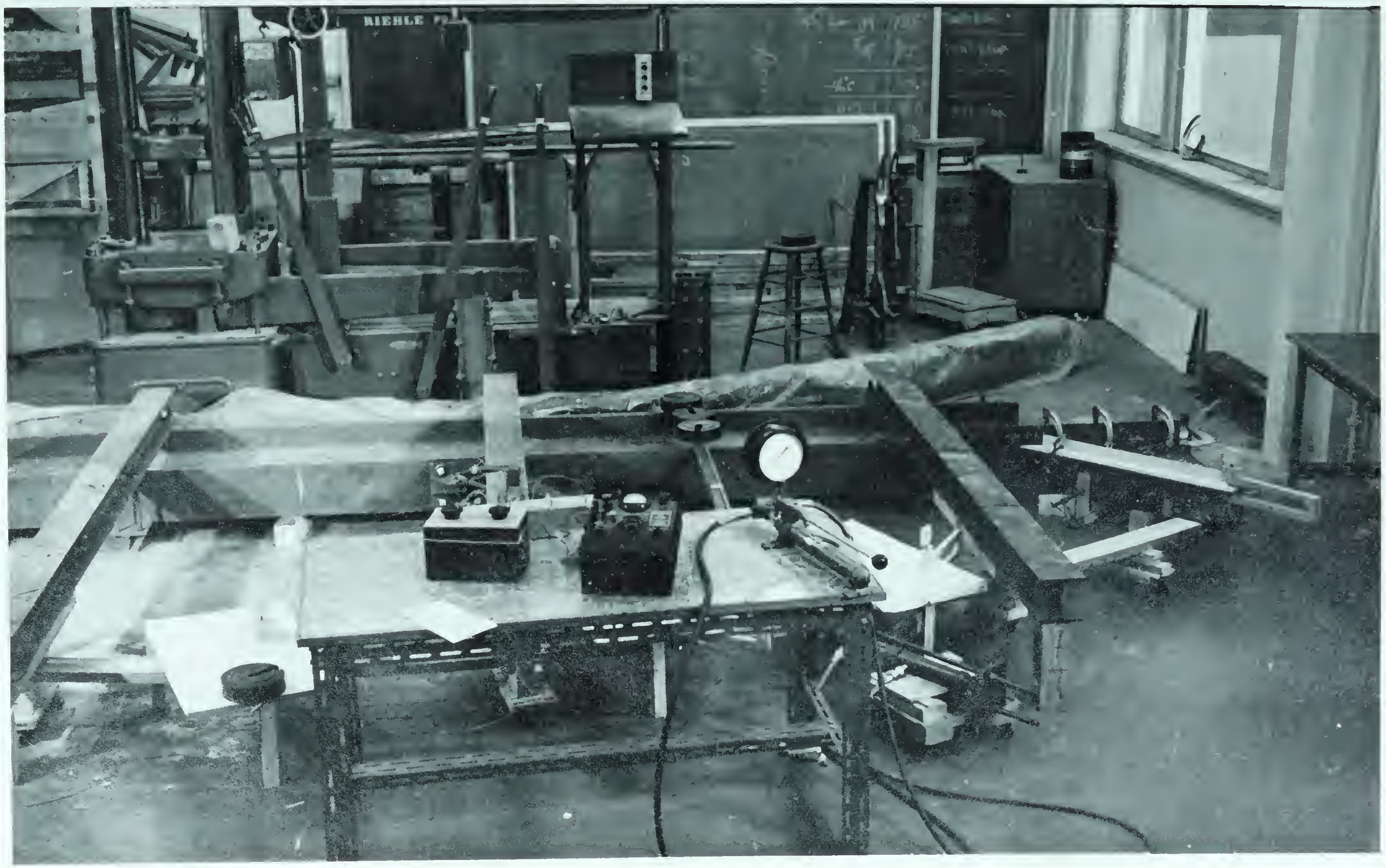


FIGURE 3. - View of Arch Testing Apparatus - Roller End.

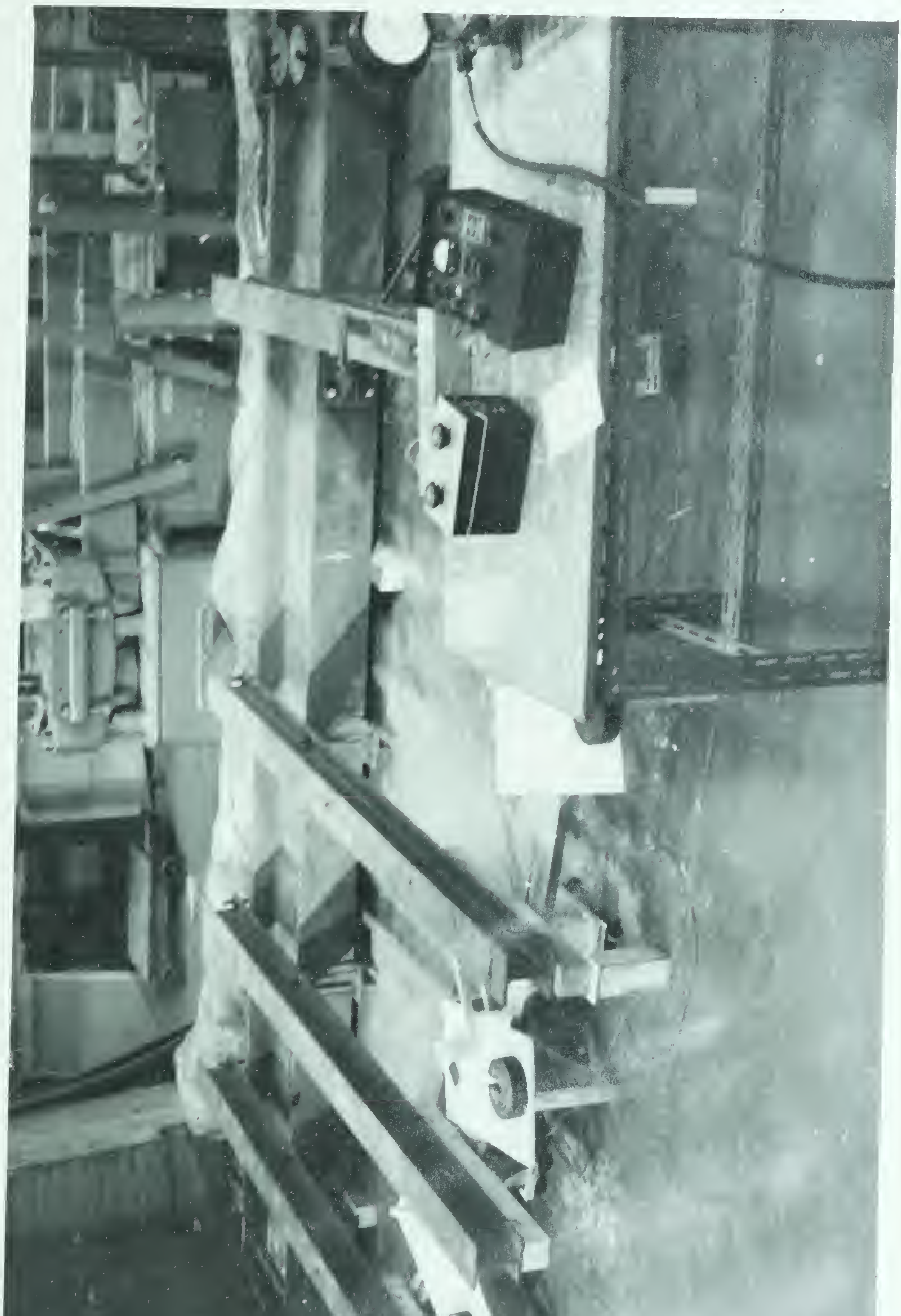


FIGURE 4. - View of Arch Testing Apparatus - Hinge End.

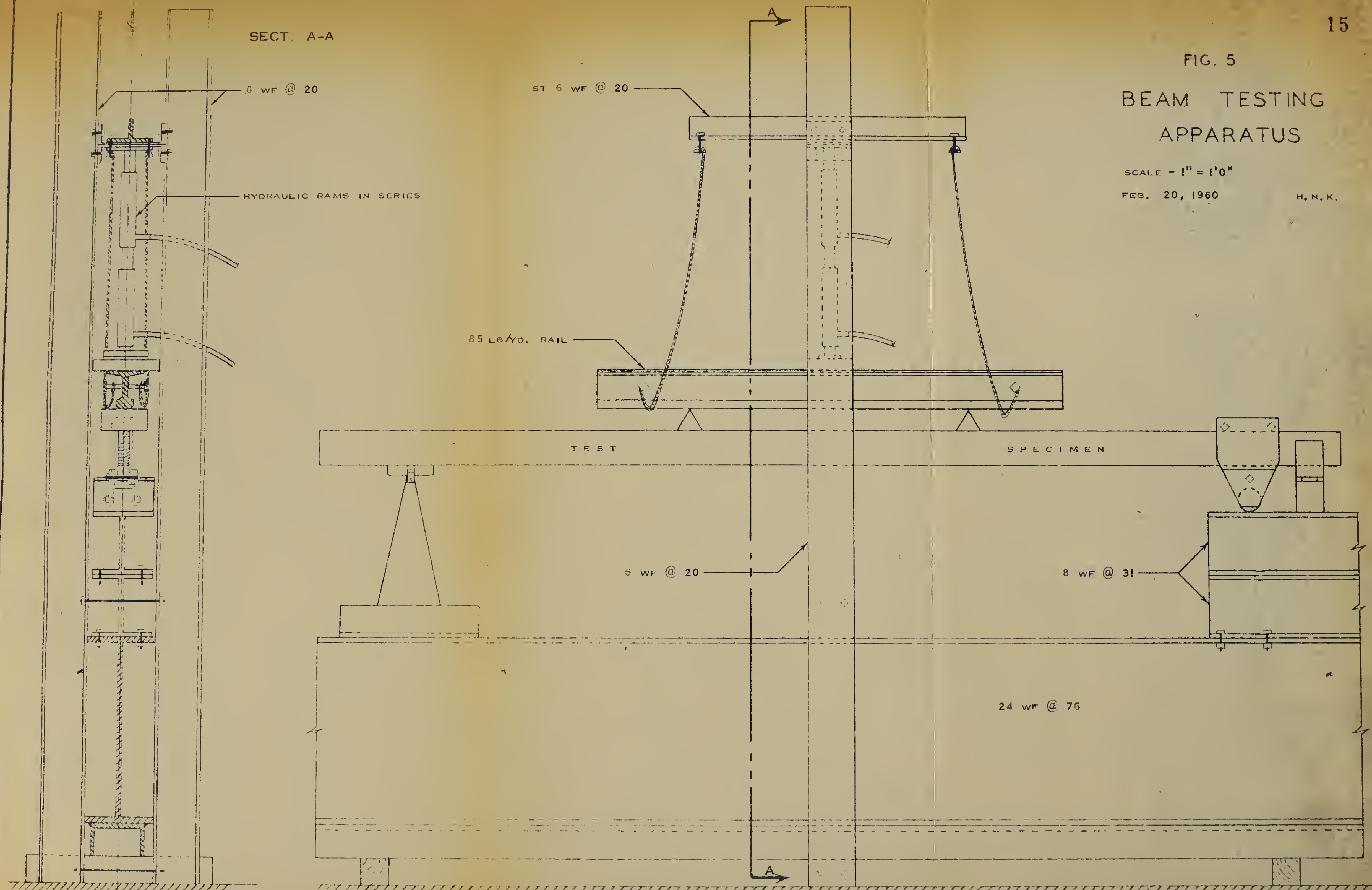


FIG. 5

BEAM TESTING APPARATUS

SCALE - 1" = 1'0"

FEB. 20, 1960

H. N. K.

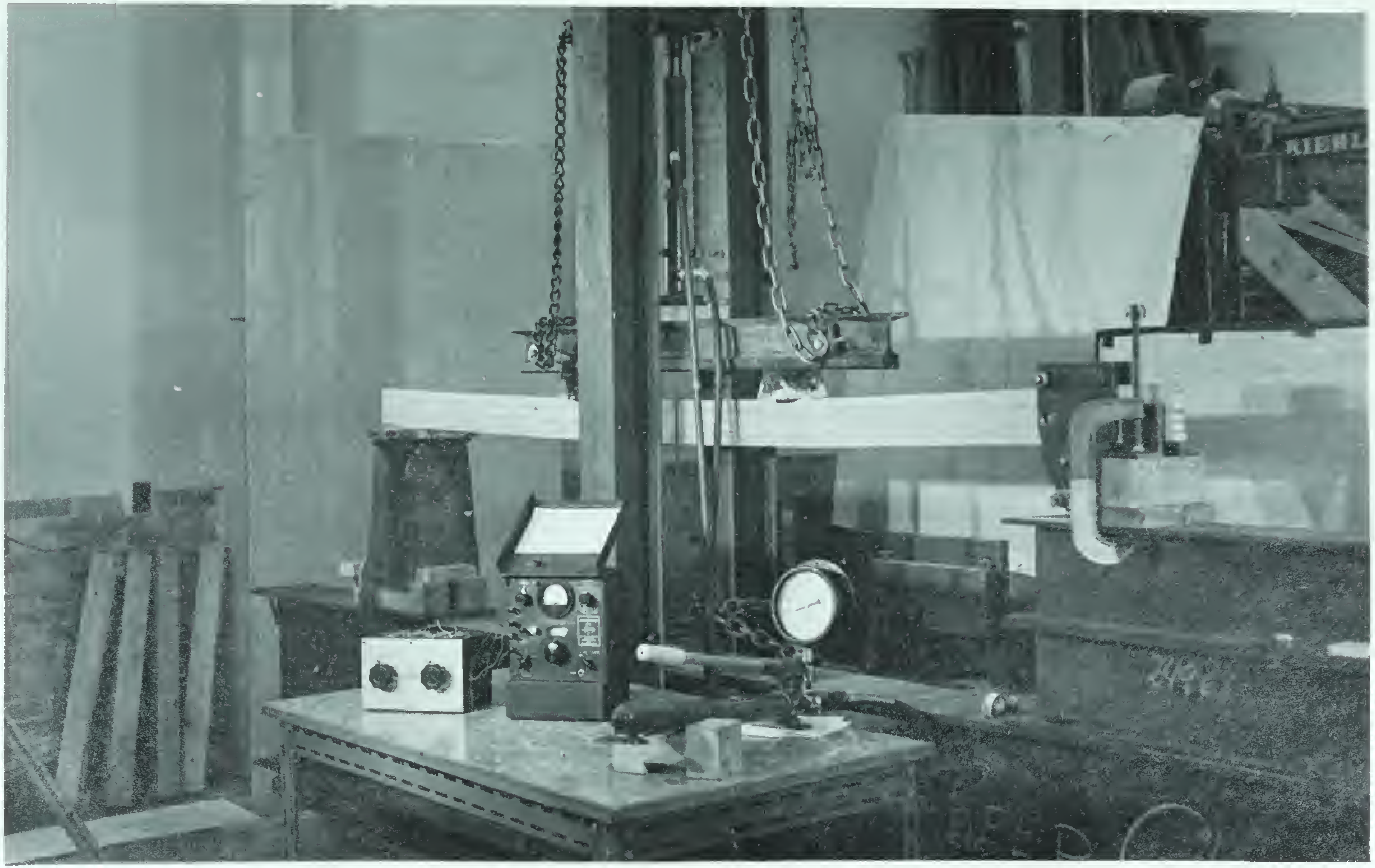


FIGURE 6. - Elevation View of Beam Testing Apparatus.

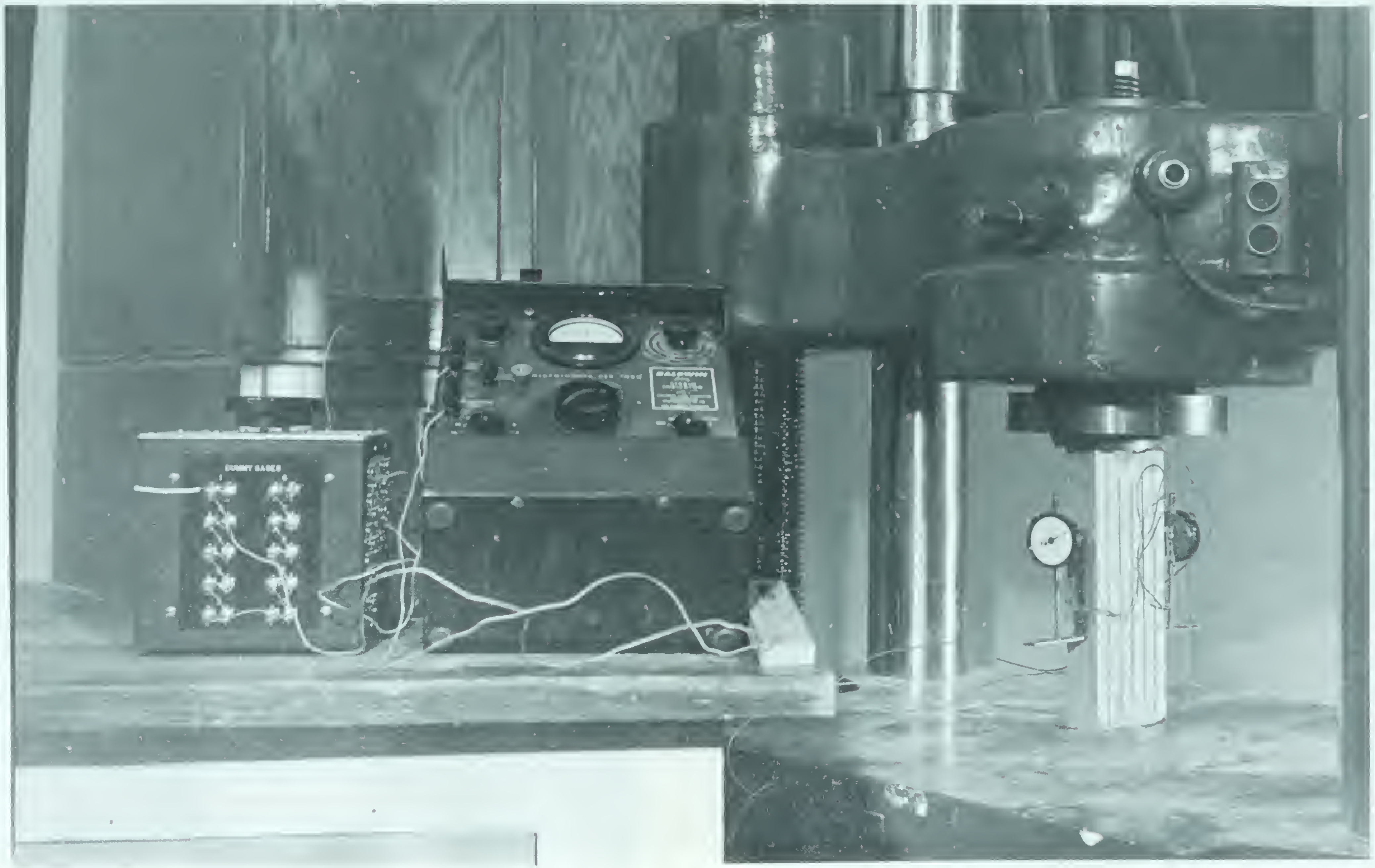


FIGURE 7. - Elevation View of Column Testing Apparatus.

FIGURE 8. - View of Self-Recording Deflection Apparatus.

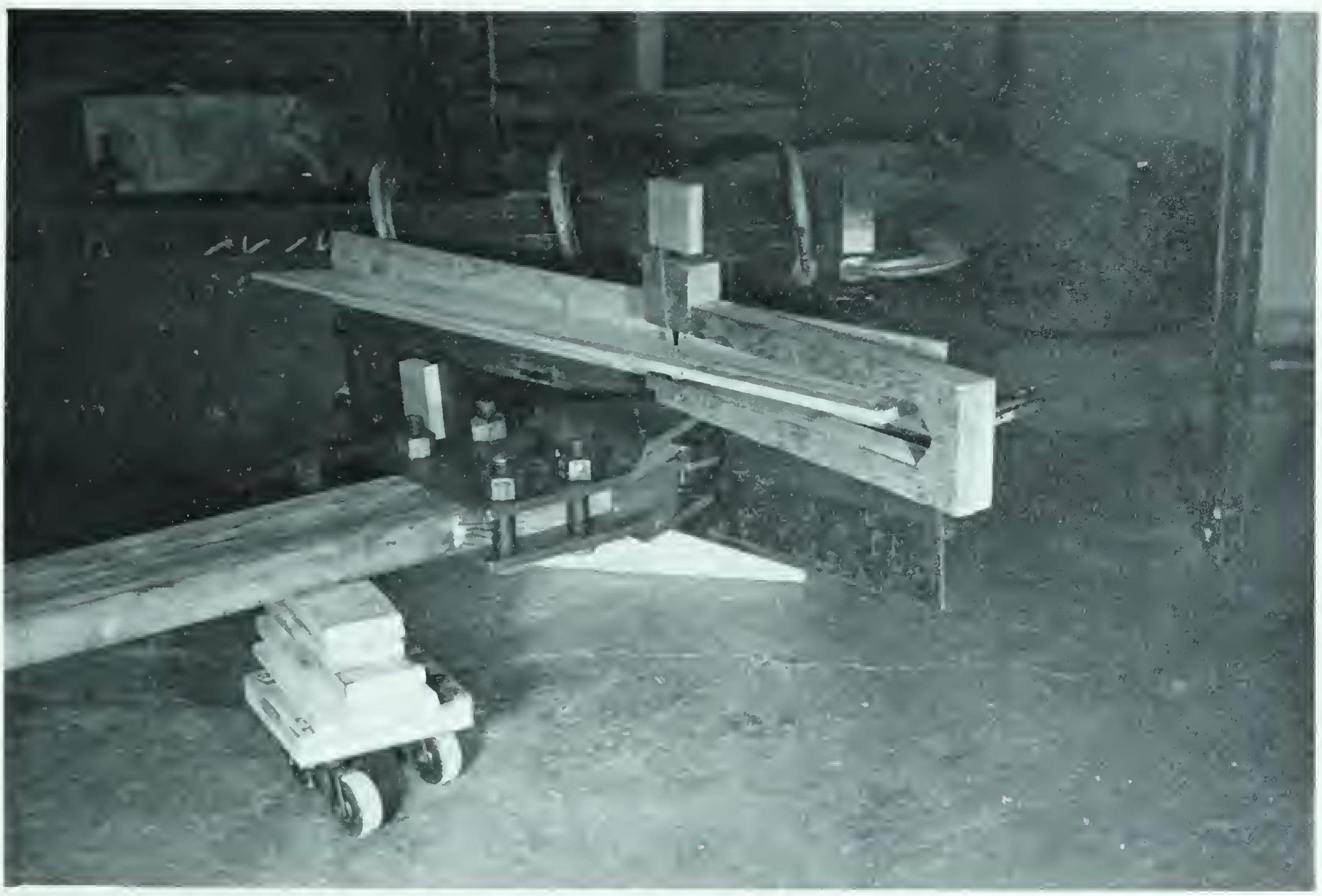


FIGURE 9. - View of Roller Reaction and Deflection Recording Apparatus.

V. PROCEDURE

1. Testing of Arch Specimens

a) Dry Specimens

Tests were conducted on six dry specimens of which three were "lefts" and three "rights". The moisture content of these specimens was about 9.5%. The specimens were trimmed at the ends to a chord length of 23.43 feet which provided a test span of 23.72 feet.

Electrical resistance strain gauges were mounted about one week prior to testing and were glued directly to the wood which had been previously sanded. An all-purpose type of household cement was used for attaching gauges. First, one application of the glue was allowed to set and form a base on the wood. A second coat was then applied on which the gauge was mounted.

The specimen complete with gauges, was placed on the flat on the rubber-castered carriers and was bolted to the hinge reaction. The roller connection was then bolted to the other end of the arch. In order to reduce friction at all locations of lateral support from the top, a coating of grease was applied to the upper surface of the specimen. Next, the wooden yokes for deflection measurement were attached and small tables, complete with graph paper, were positioned. The graph paper on these tables was oriented at such an angle that one axis represented the vertical direction (i.e. direction parallel to the roller plane) while the other axis represented the horizontal direction. Recording ball-point pens were then inserted into the yokes and pressure was applied to them by stretching rubber bands over them. All soldered strain gauge connections were checked with an ohm meter to locate any

defective connections. The specimen was then ready to be tested.

In order to eliminate any "looseness" that might exist in the system, a small load was applied to the specimen before initial readings were taken. After all initial strain readings were taken and the initial positions of the deflection recording pens marked on the graphs, the load was increased to 100 pounds and from thereon was applied in increments of 100 pounds every 15 minutes until failure occurred. At each load increment, the position of the recording pens was marked on the graphs and strain readings were taken. Appreciable "drift" was observed in all gauges immediately after each was connected to the indicator through the switching unit. It was, therefore, necessary to allow about one minute before each reading was taken. After failure of the specimen occurred, the details of the fracture were noted. Two 2" x 2-1/4" x 1-1/2" samples were cut at each of three locations (approximately the quarter points) in the arch. One of these samples contained the three bottom laminates while the other contained the three top laminates. The samples were labelled and weighed on a free arm balance. They were then placed in an oven at a temperature of 100° C. and dried for a period of 24 hours after which they were weighed again. Moisture contents were then determined. After the oven dry weight of the sample had been obtained the samples were immersed in liquid paraffin to provide an impermeable water surface on the sample. The paraffin coated samples were then weighed in air to determine the weight of paraffin on the sample. Next, they were weighed in water and their volume was determined. The density and specific gravity were then calculated.

b) Wet Specimens

Six wet specimens, of which three were "rights" and three "lefts", were tested. A high average moisture content of 28.6% was obtained by wrapping the specimens in damp burlap sacks and covering them with polyethylene sheet to prevent evaporation losses. The specimens were kept in this condition for more than two months before testing.

Approximately 41 hours prior to actual testing time, the specimens were removed from the moist atmosphere and allowed to dry at room temperature and humidity (70° F. and relative humidity of 65%). Approximately 23 hours later electric resistance strain gauges were mounted in the same position as for the dry specimens. The procedure was somewhat different in that the gauges were not mounted directly on the wood. To provide a waterproof barier for the strain gauge, a thin celluloid strip was first attached with waterproof glue to the sanded wood surface. An hour later, a coating of all-purpose household glue was applied to the celluloid and the strain gauge was then mounted. The specimen was tested 17 hours later.

The actual testing procedure was identical to that already described for the dry specimens.

2. <u>Testing of Beam Specimens</u>

a) <u>Dry Specimens</u>

Six beam specimens having an average moisture content of about 9.0% were tested to failure under third point loading on a 9.0 foot test span. Strains on the top and bottom faces at midspan were measured by SR-4 type A-3 electric resistance strain gauges. Centerline deflection was obtained by taking readings with a precise level on a steel scale attached to the side of the specimen.

After initial readings had been taken for strains and deflection the five foot loading rail was lowered onto the third points. Strain readings were taken at this load which amounted to 155 pounds. Load was then applied by jacking in increments of 200 pounds every 10 minutes until failure occurred. Strains and centerline deflection were observed for each load increment.

After failure had occurred, two samples were cut from the beam specimen for the purpose of determining moisture content and specific gravity.

b) <u>Wet Specimens</u>

Six wet specimens having an average moisture content of about 18.5% were tested. The increased moisture contents were obtained by using the same method as for the arch specimens but for a shorter period of time. The beam specimens were subjected to severe moisture conditions for about three and one-half weeks before being tested.

Specimens were exposed to room conditions for 38 hours prior to testing and strain gauges were mounted after 15 hours had elapsed. The gauge mounting procedure was identical to that used for the wet arch specimens.

The testing procedure was identical to that used in the testing of the dry specimens.

3. Testing of Column Specimens

a) Dry Specimens

Six column specimens having an average moisture content of about 8.6% were tested in axial compression. Strain observations were taken by means of electrical resistance strain gauges and mechanical Mercer dial gauges.

Two SR-4 strain gauges were mounted on opposite sides parallel to the longitudinal axis and at mid-height of the specimen. Two mechanical Mercer gauges were mounted for comparison purposes by means of metal clips and wood screws on a 3.0 inch gauge length.

Prior to testing, the specimen was capped with a sulfur fire clay mixture in an attempt to eliminate any eccentricity of loading that might otherwise occur. The specimen was then carefully centered in the testing machine and initial strain readings were taken. Axial load was applied in increments of 4,000 pounds every 10 minutes up to failure. Strain measurements on both the SR-4 and Mercer gauges were taken at each load increment. When a load of 40,000 pounds was reached, the Mercer gauges were removed.

After failure had occurred, two 2" x 2-1/4" x 1-1/2" samples were cut from opposite faces for determination of moisture content and specific gravity.

b) Wet Specimens

Six specimens having an average moisture content of about 15.7% were tested. Higher moisture contents were obtained in exactly

the same manner as used for the beam specimens. Specimens were exposed to room conditions for 38 hours prior to testing and strain gauges were mounted after 15 hours had elapsed.

The test procedure was identical to that used in the testing of the dry column specimens.

VI. RESULTS

Results of the tests are presented in graphical form on the following Figures:

	FIGURE	DESCRIPTION
	12A to 12H	Load vs. Strain - Dry Arch Specimens.
	13A to 13H	Load vs. Strain - Wet Arch Specimens.
	14	Sample Self-Recorded Deflection Graph.
	15	Typical Deflection Graph Showing Relative Movement at all Positions.
	16A to 16F	Load vs. Deflection - Dry Arch Tests.
	17A to 17F	Load vs. Deflection - Wet Arch Tests.
	18	Ultimate Load vs. Moisture Content - Arch Specimens.
*	30A and 30B	Load vs. Strain - Dry Beam Tests.
*	31A and 31B	Load vs. Strain - Wet Beam Tests.
	32A and 32B	Load vs. Deflection - Dry Beam Tests.
	33A and 33B	Load vs. Deflection - Wet Beam Tests.
	34	Ultimate Load vs. Moisture Content - Beam Specimens.
**	37A to 37F	Load vs. Strain - Dry Column Tests.
**	38A to 38D	Load vs. Strain - Wet Column Tests.
	39	Ultimate Load vs. Moisture Content - Column Specimens.

The calibration curve shown on Figure 10 was used to convert all gauge readings to actual load values.

* The letters T and B following the beam specimen numbers in Figures 30A, 30B, 31A and 31B refer to the top and bottom surfaces of the beam respectively.

** The numbers 1 and 2 following the column specimen numbers in Figures 37A to 37F and in 38A to 38D are used to differentiate between the two gauges on the same specimen.

Views of the failures that occurred in the test specimens are shown in the following Figures:

FIGURE	DESCRIPTION
19 to 29	Views of failures in the arch specimens.
35 and 36	Views of failures in the beam specimens.
40 and 41	Views of failures in the column specimens.

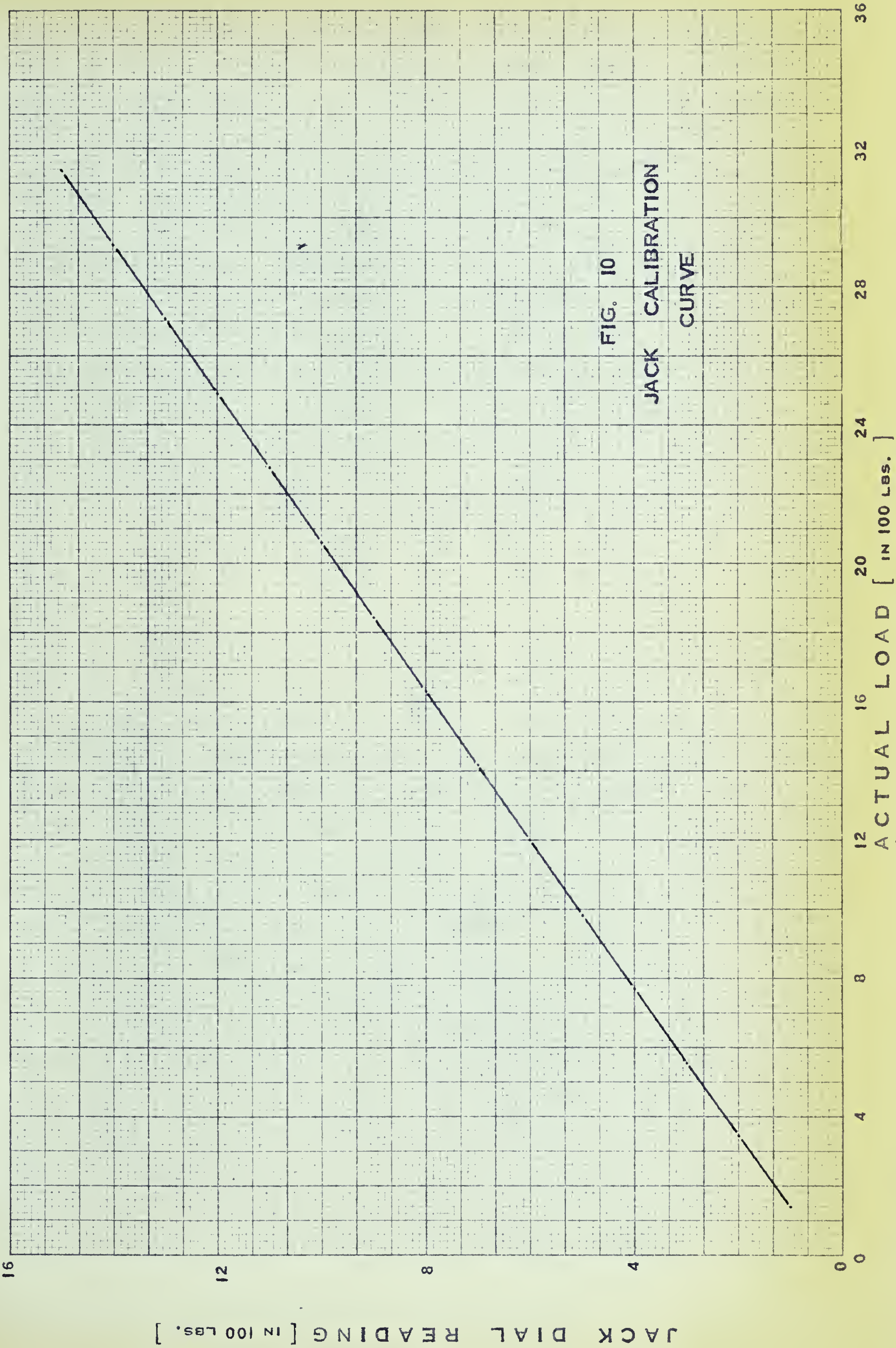
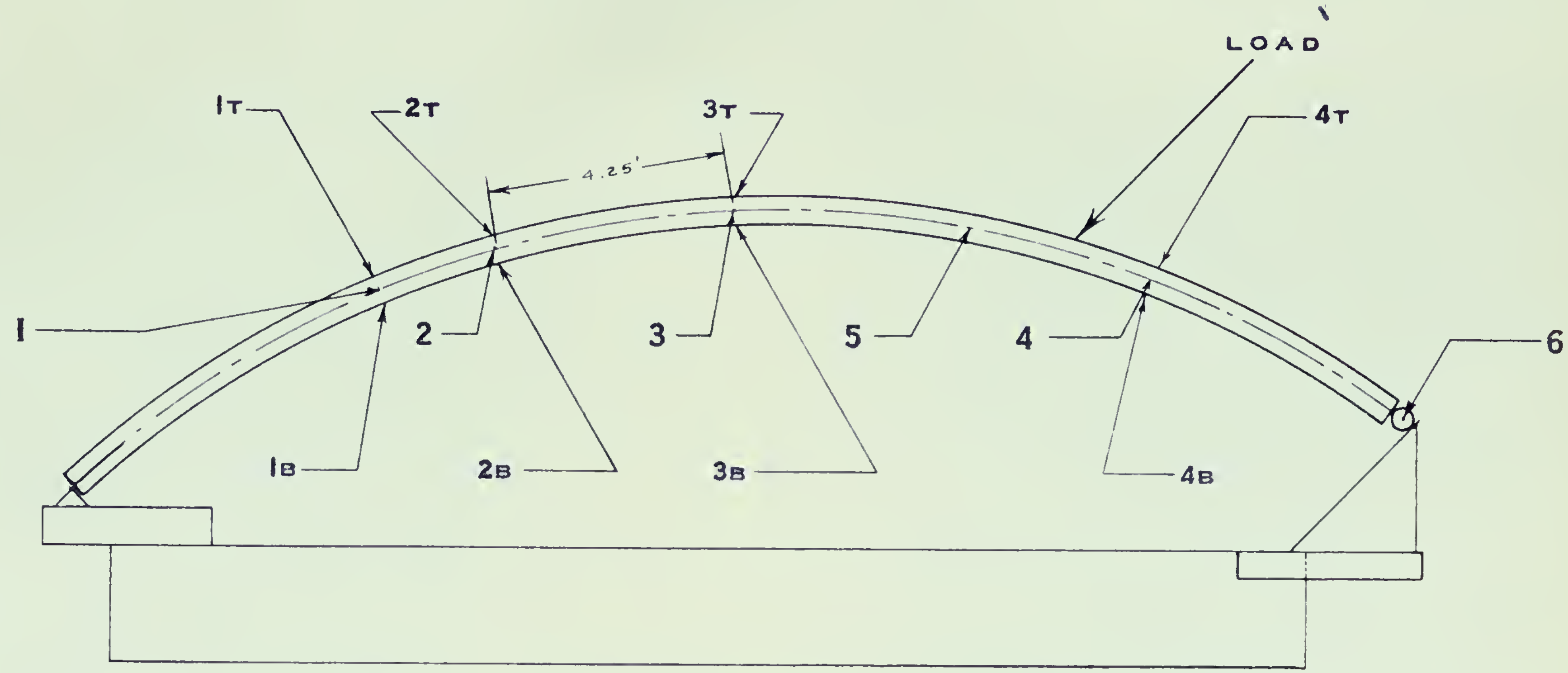


FIG. 10
JACK CALIBRATION CURVE



LEGEND

STRAIN GAUGE POSITIONS

1T - 1/4 POINT HINGE [TOP]
1B - 1/4 POINT HINGE [BOTTOM]
2T - MAXIMUM MOMENT [TOP]
2B - MAXIMUM MOMENT [BOTTOM]
3T - CENTERLINE [TOP]
3B - CENTERLINE [BOTTOM]
4T - 20" FROM LOAD [TOP]
4B - 20" FROM LOAD [BOTTOM]

DEFLECTION POSITIONS ON CENTERLINE

1 - 1/4 POINT HINGE
2 - MAXIMUM MOMENT
3 - CENTERLINE
4 - 20" FROM LOAD POINT
5 - 20" FROM LOAD POINT
6 - ROLLER REACTION

FIG. 11

LOCATION OF STRAIN GAUGES AND DEFLECTION YOKES

NOT TO SCALE

SUBSCRIPT T DENOTES TOP SURFACE OF SPECIMEN
SUBSCRIPT B DENOTES BOTTOM SURFACE OF SPECIMEN

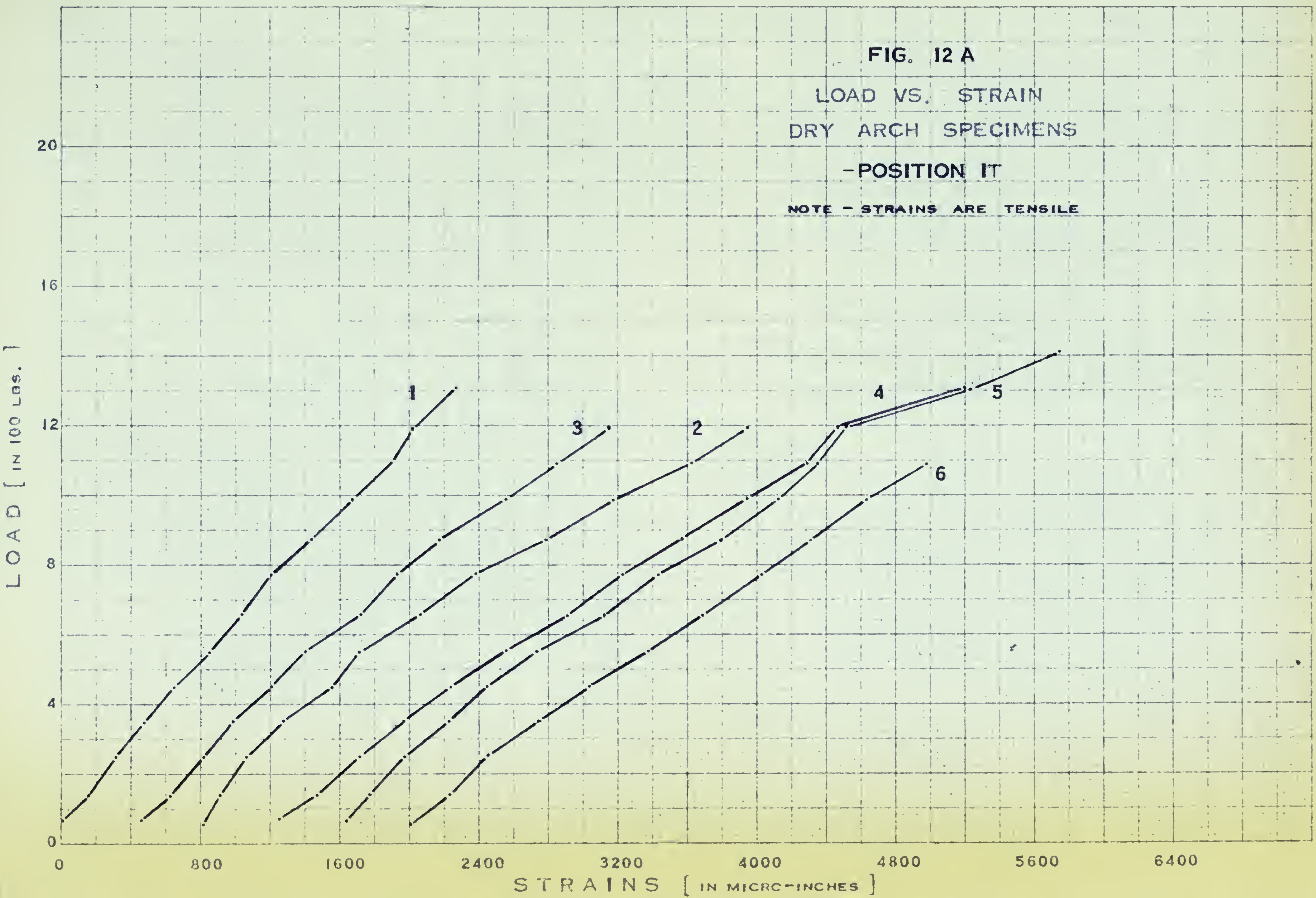


FIG. 12 A
LOAD VS. STRAIN
DRY ARCH SPECIMENS
-POSITION IT
NOTE - STRAINS ARE TENSILE
1
2
3
4
5
6
LOAD [IN 100 LBS.]
0
4
8
12
16
20
STRAINS [IN MICRC-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400

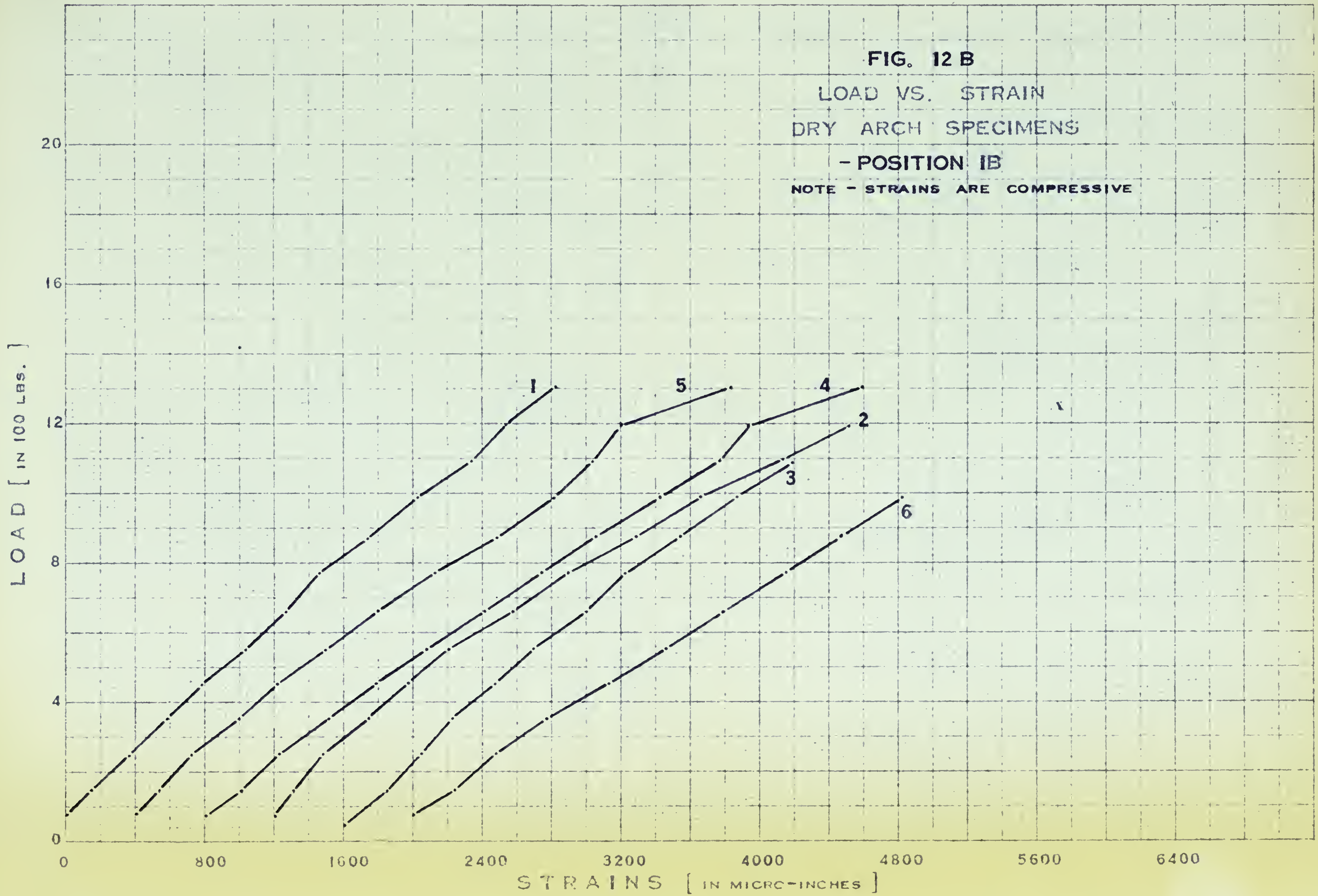


FIG. 12 B
LOAD VS. STRAIN
DRY ARCH SPECIMENS
- POSITION IB
NOTE - STRAINS ARE COMPRESSIVE
1
5
4
2
3
6
LOAD [IN 100 LBS.]
0
4
8
12
16
20
0
800
1600
2400
3200
4000
4800
5600
6400
STRAINS [IN MICRO-INCHES]

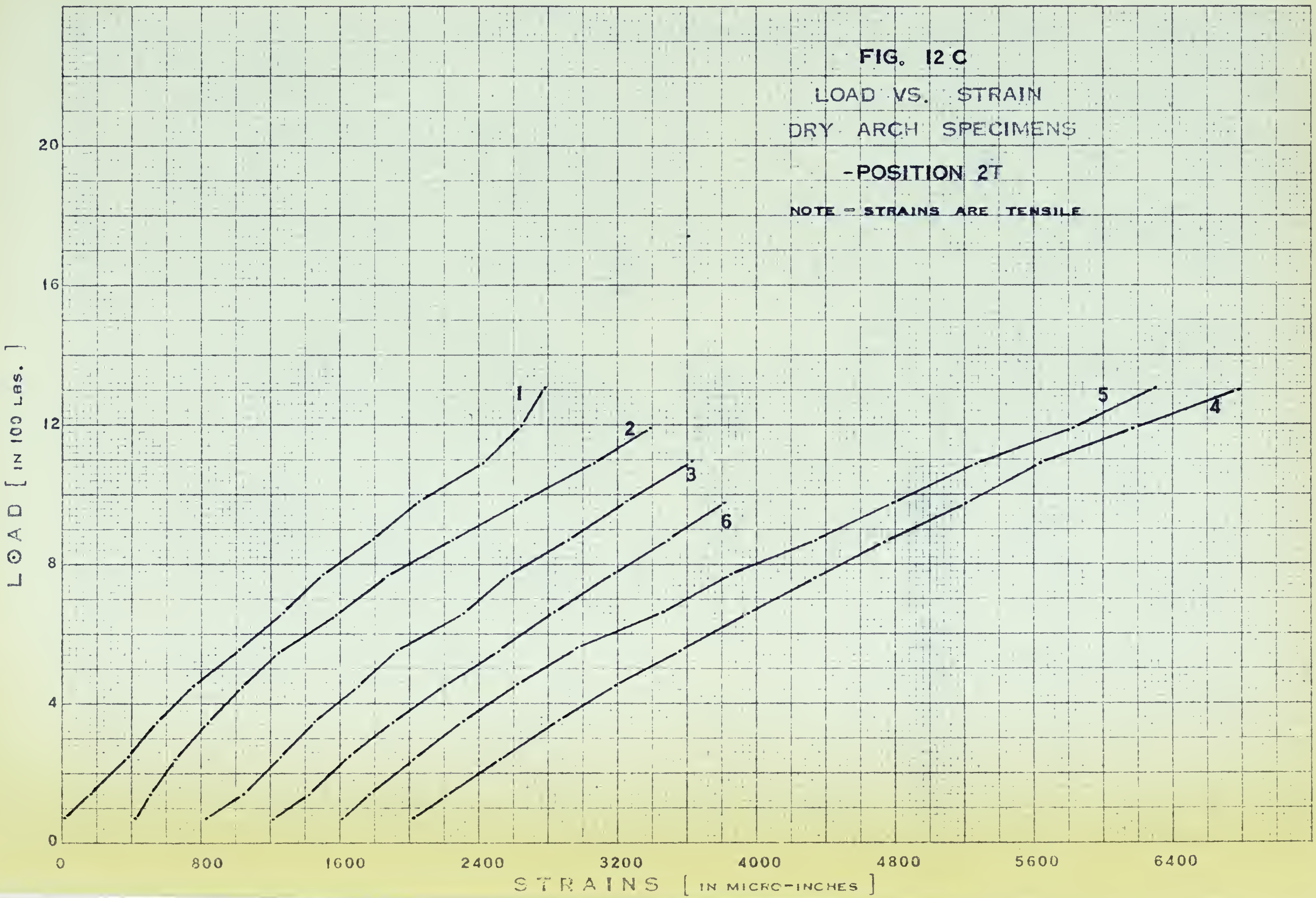


FIG. 12 C
LOAD VS. STRAIN
DRY ARCH SPECIMENS
-POSITION 2T
NOTE - STRAINS ARE TENSILE
1
2
3
4
5
6
LOAD [IN 100 LBS.]
0
4
8
12
16
20
STRAINS [IN MICRO-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400

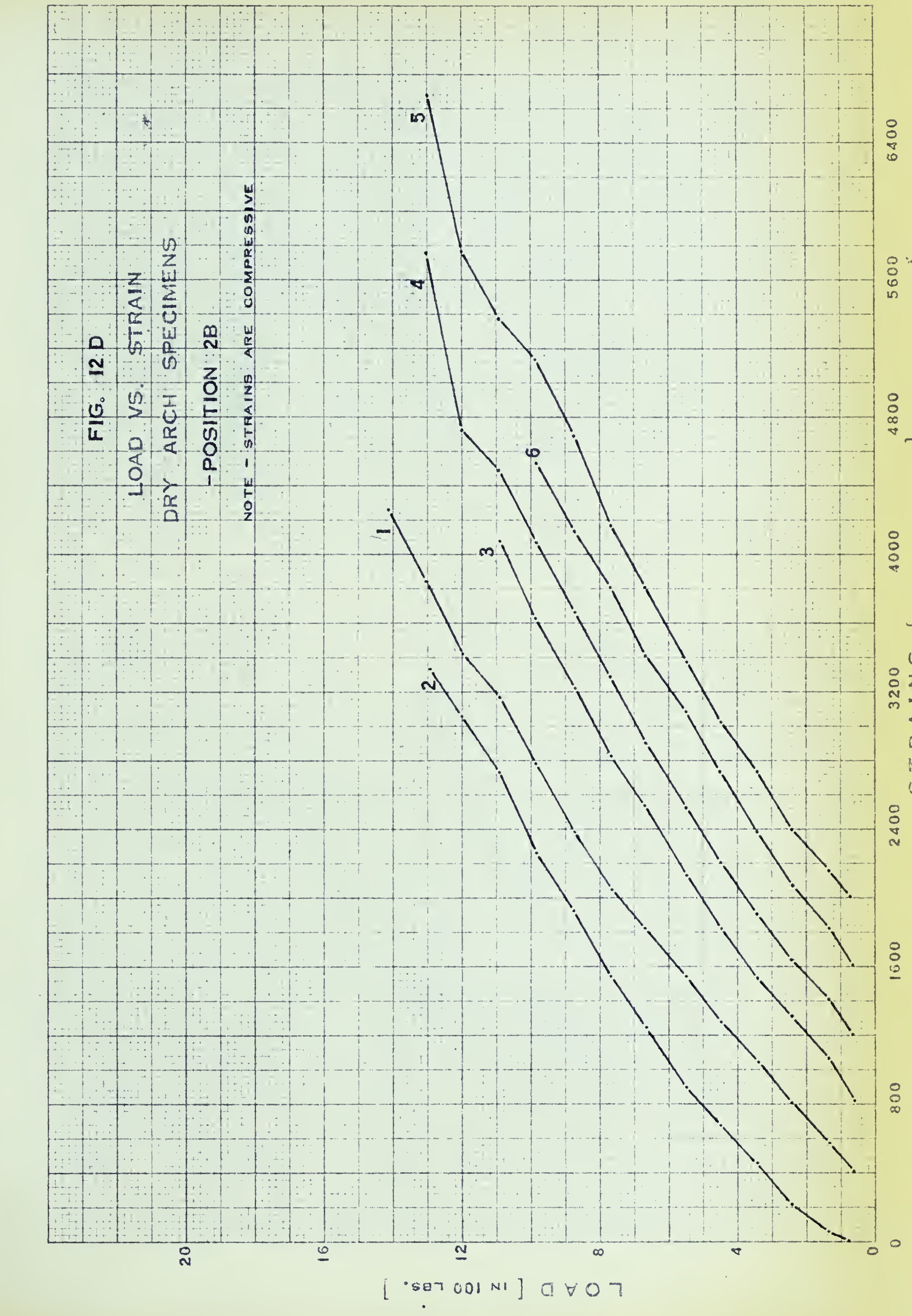


FIG. 12 D
LOAD VS. STRAIN
DRY ARCH SPECIMENS
-POSITION 2B
NOTE - STRAINS ARE COMPRESSIVE
1
2
3
4
5
6
0
4
8
12
16
20
LOAD [IN 100 LBS.]
0
800
1600
2400
3200
4000
4800
5600
6400

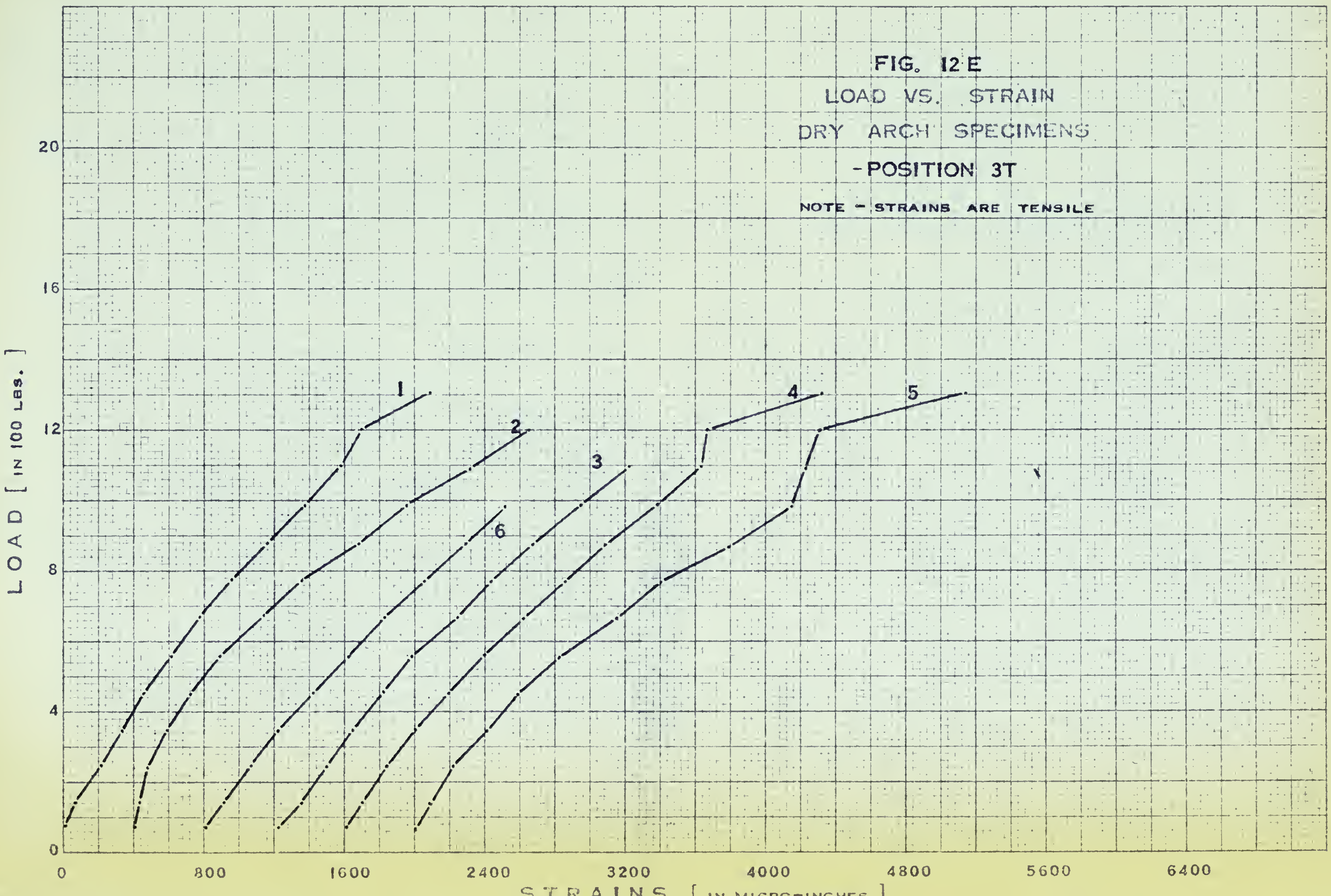


FIG. 12 E
LOAD VS. STRAIN
DRY ARCH SPECIMENS
- POSITION 3T
NOTE - STRAINS ARE TENSILE
1
2
3
4
5
6
20
16
12
8
4
0
800
1600
2400
3200
4000
4800
5600
6400
LOAD [IN 100 LBS.]
STRAINS [IN MICRO-INCHES]

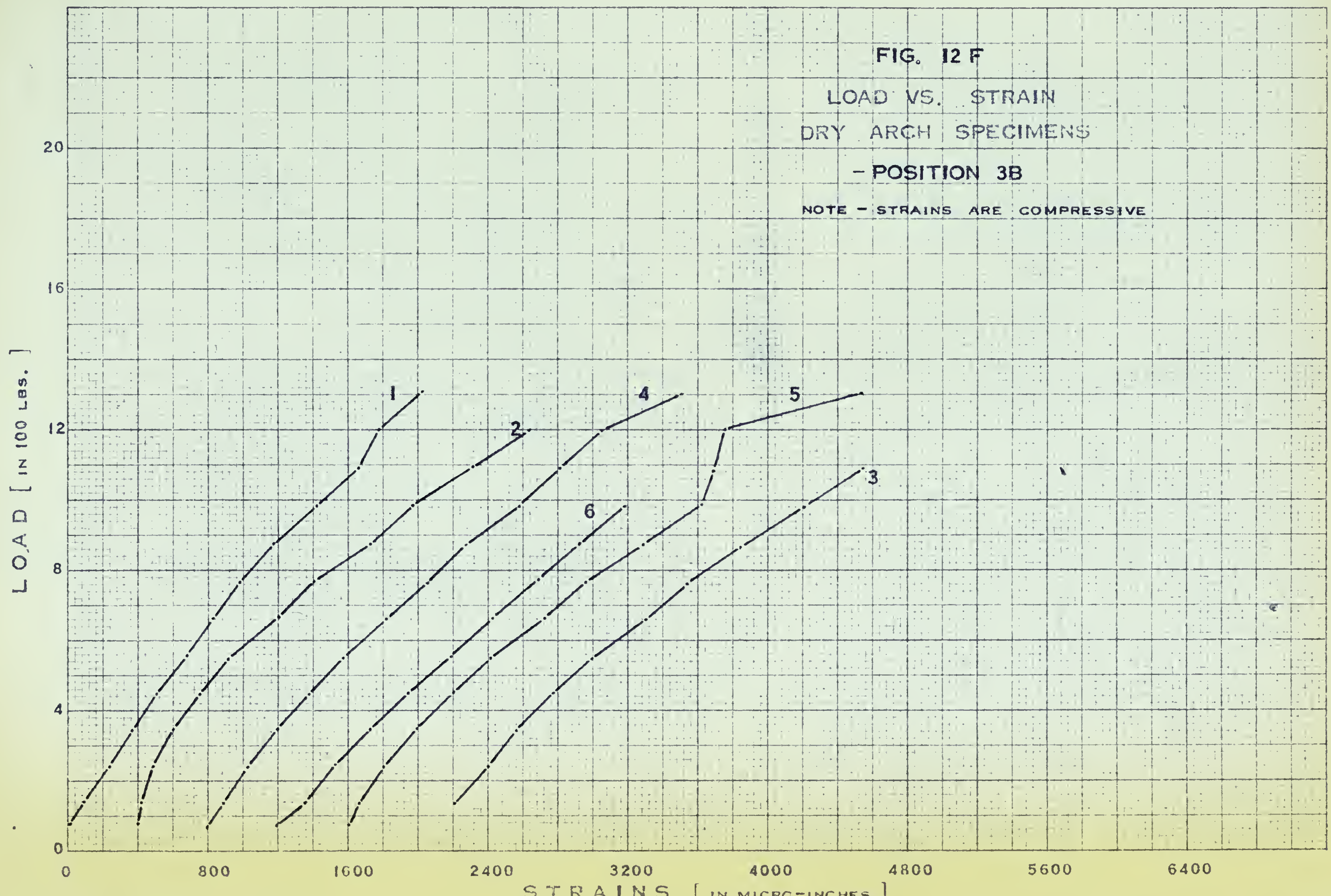


FIG. 12 F
LOAD VS. STRAIN
DRY ARCH SPECIMENS
- POSITION 3B
NOTE - STRAINS ARE COMPRESSIVE
1
2
3
4
5
6
LOAD [IN 100 LBS.]
0
4
8
12
16
20
STRAINS [IN MICRC-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400

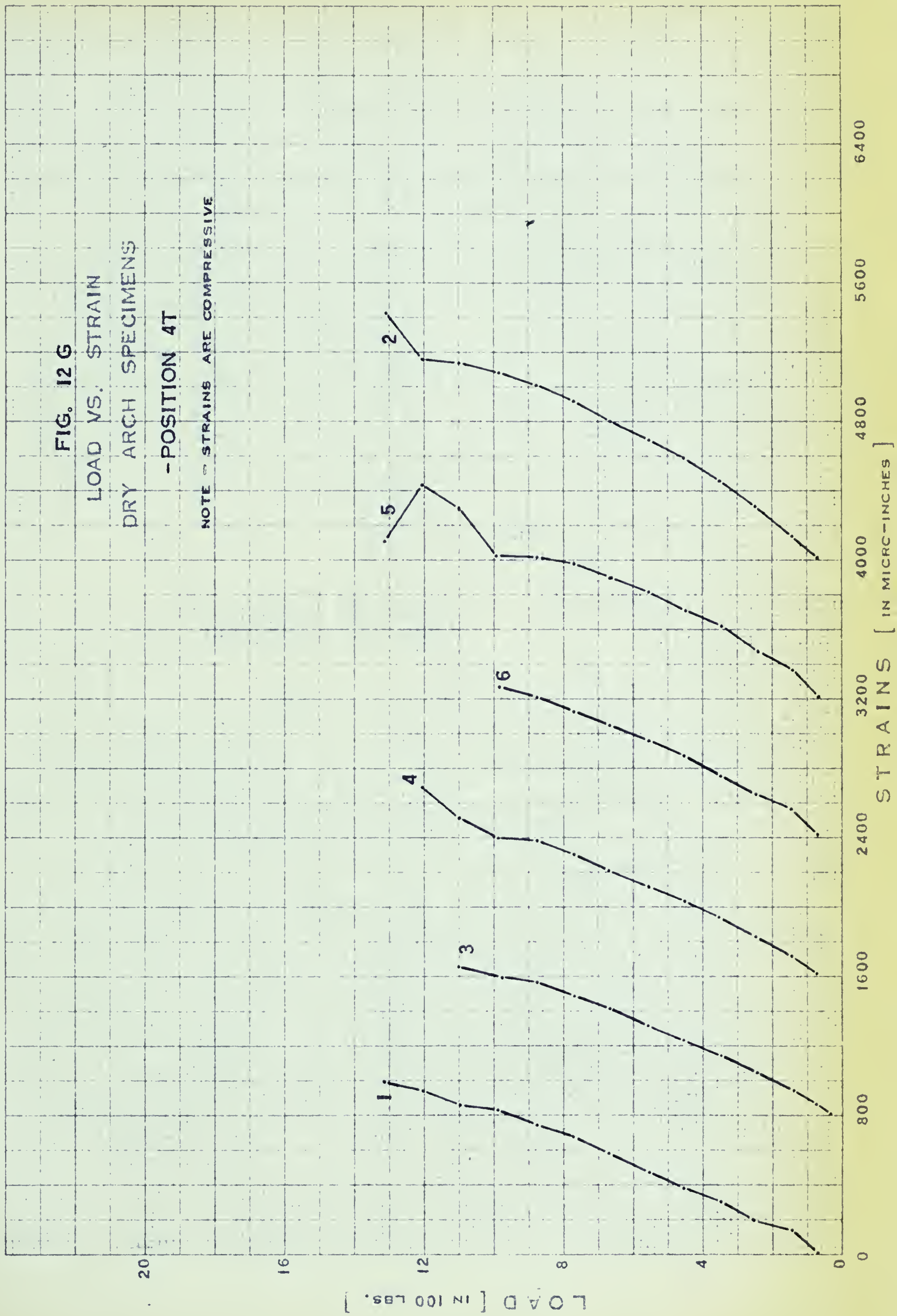


FIG. 12 G
LOAD VS. STRAIN
DRY ARCH SPECIMENS
-POSITION 4T
NOTE - STRAINS ARE COMPRESSIVE
1
2
3
4
5
6
0
800
1600
2400
3200
4000
4800
5600
6400
STRAINS [IN MICRO-INCHES]
0
4
8
12
16
20
LOAD [IN 100 LBS.]

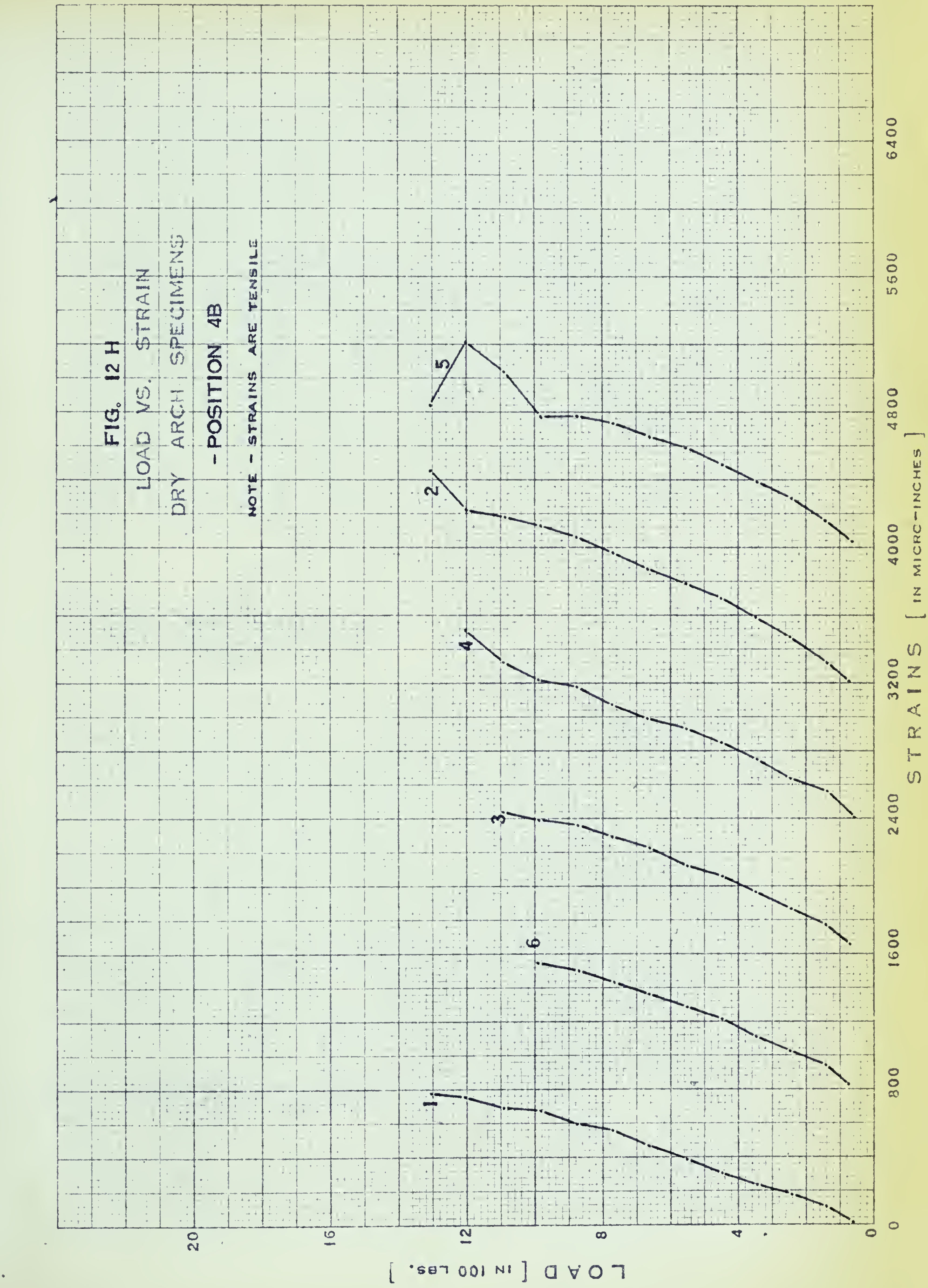


FIG. 12 H
LOAD VS. STRAIN
DRY ARCH SPECIMENS
- POSITION 4B
NOTE - STRAINS ARE TENSILE
1
2
3
4
5
6
0
800
1600
2400
3200
4000
4800
5600
6400
STRAINS [IN MICRO-INCHES]
0
4
8
12
16
20
LOAD [IN 100 LBS.]

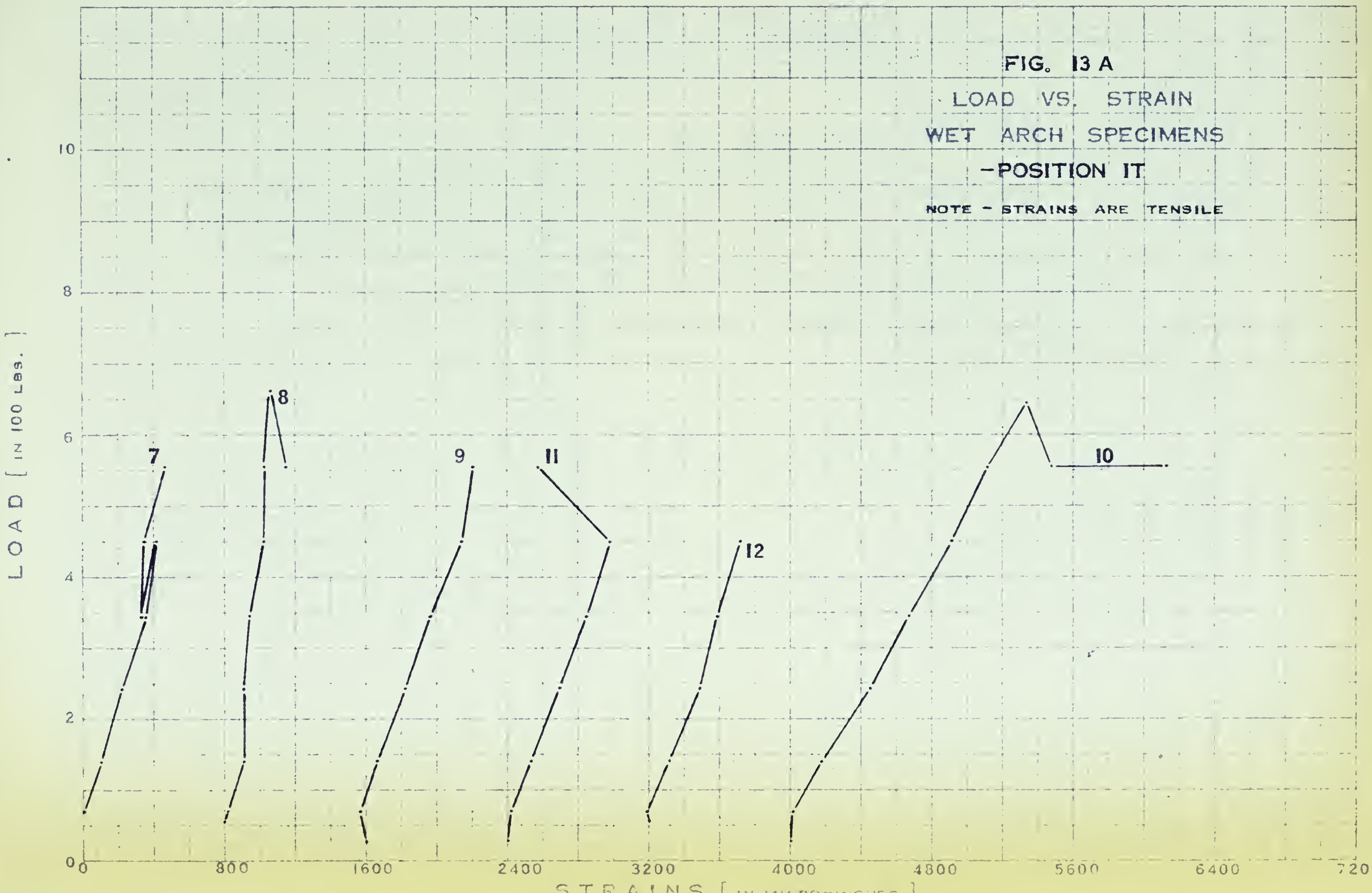


FIG. 13 A
LOAD VS. STRAIN
WET ARCH SPECIMENS
-POSITION IT
NOTE - STRAINS ARE TENSILE
7
8
9
11
12
10
LOAD [IN 100 LBS.]
0
2
4
6
8
10
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]

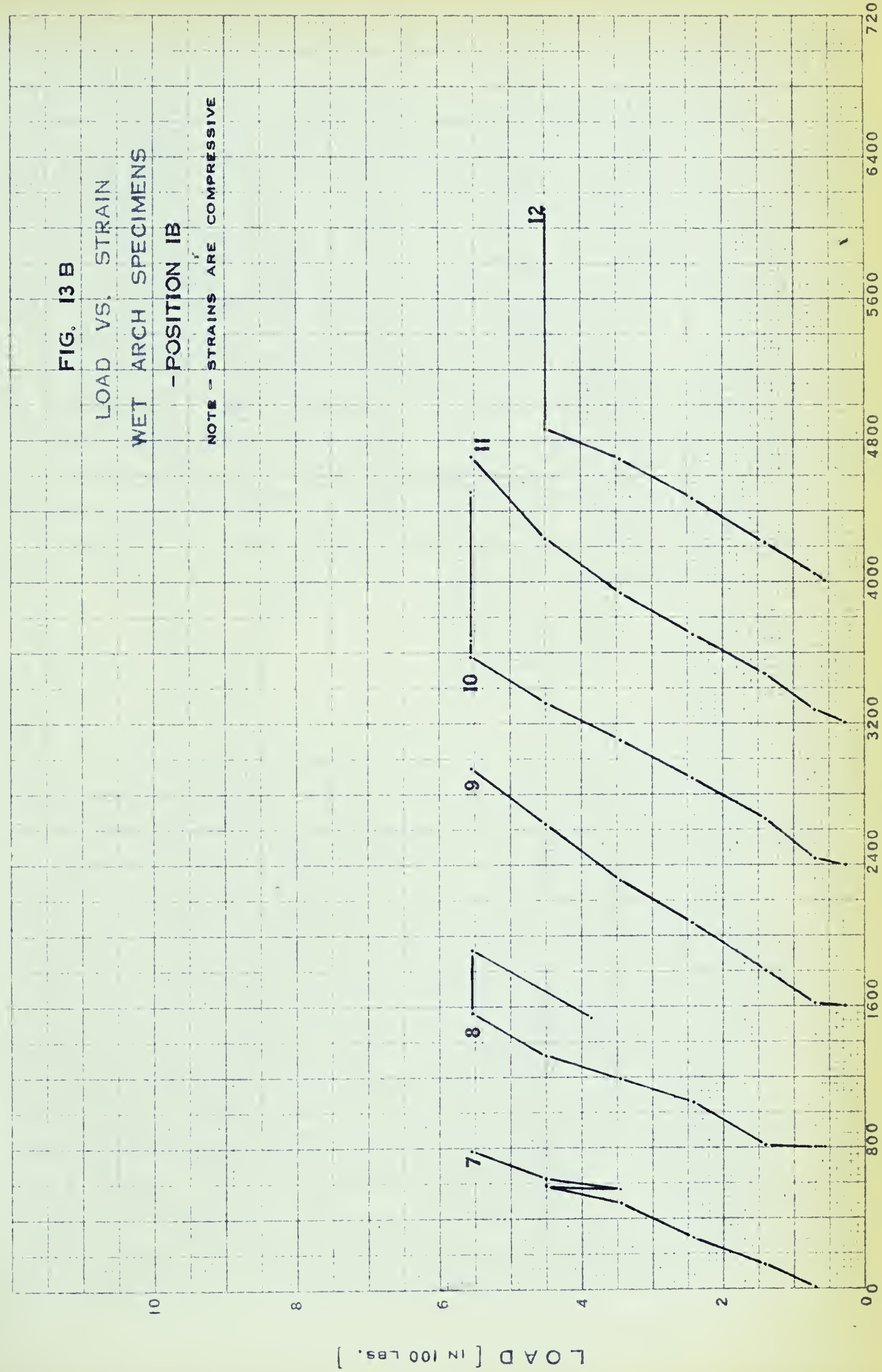


FIG. 13 B
LOAD VS. STRAIN
WET ARCH SPECIMENS
- POSITION IB
NOTE - STRAINS ARE COMPRESSIVE
7
8
9
10
11
12
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
2
4
6
8
10
LOAD [IN 100 LBS.]

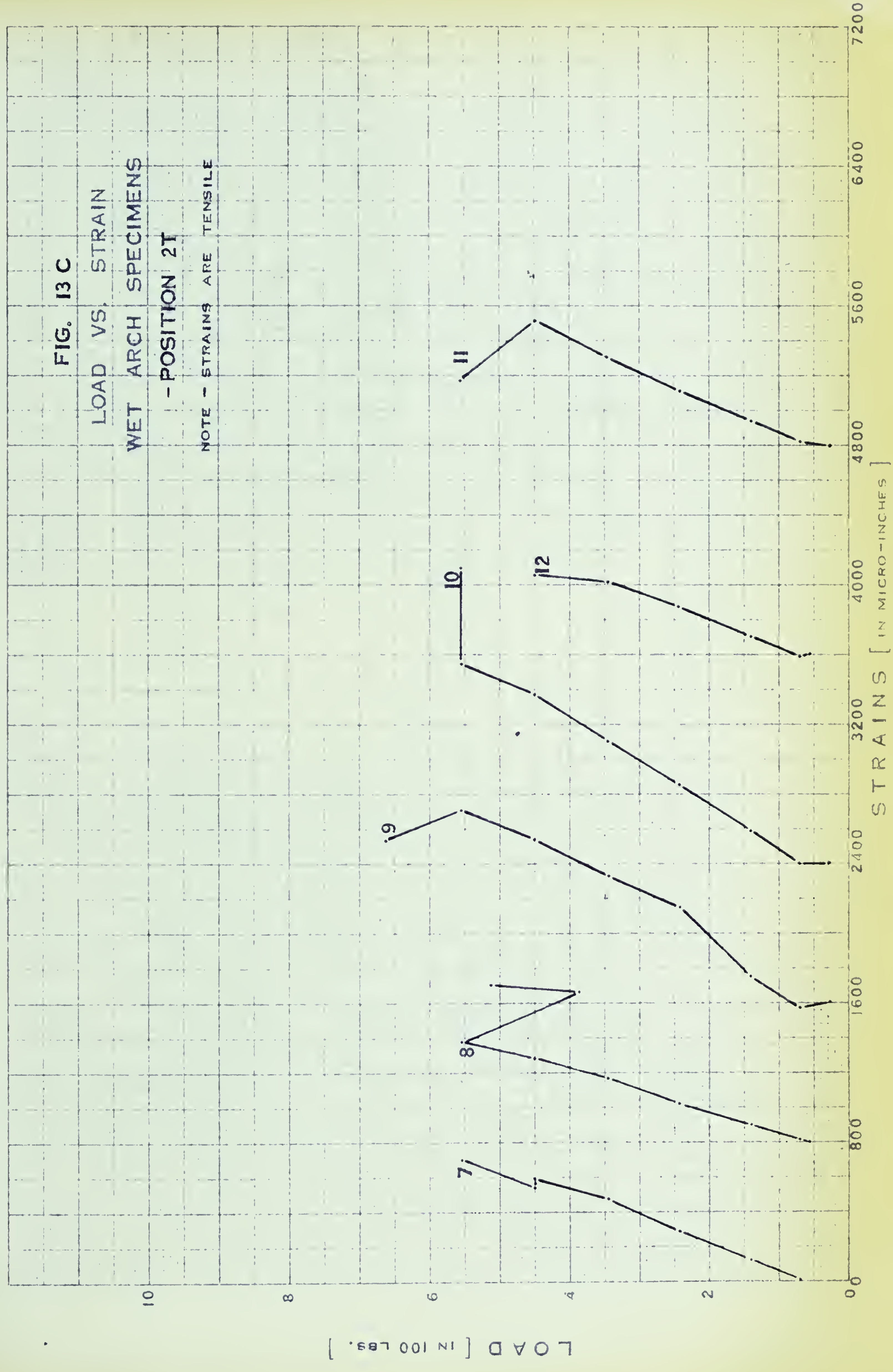


FIG. 13 C
LOAD VS. STRAIN
WET ARCH SPECIMENS
- POSITION 2T
NOTE - STRAINS ARE TENSILE
7
8
9
10
11
12
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
2
4
6
8
10
LOAD [IN 100 LBS.]

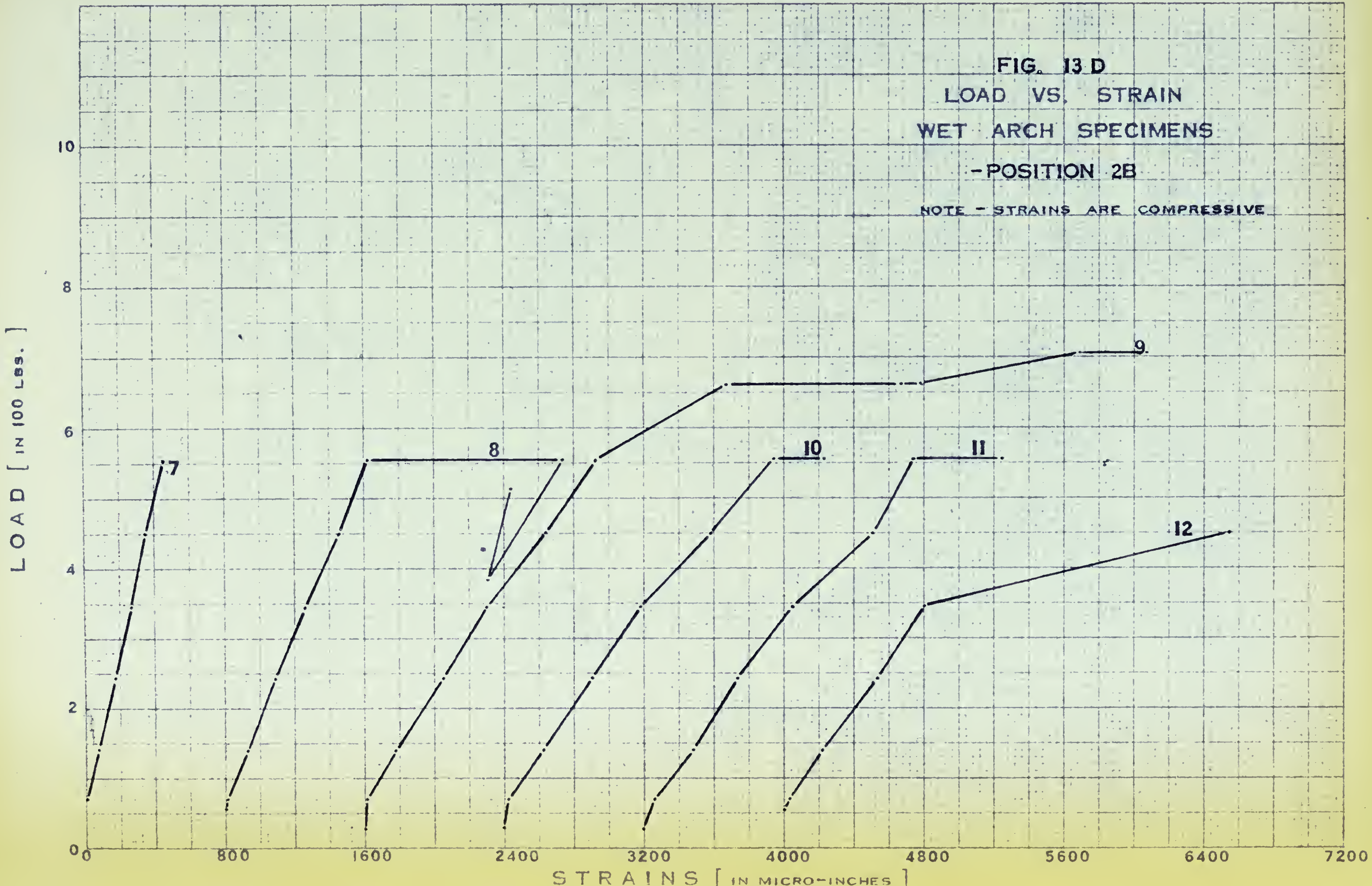


FIG. 13 D
LOAD VS. STRAIN
WET ARCH SPECIMENS
-POSITION 2B
NOTE - STRAINS ARE COMPRESSIVE
7
8
9
10
11
12
0
2
4
6
8
10
0
800
1600
2400
3200
4000
4800
5600
6400
7200
LOAD [IN 100 LBS.]
STRAINS [IN MICRO-INCHES]

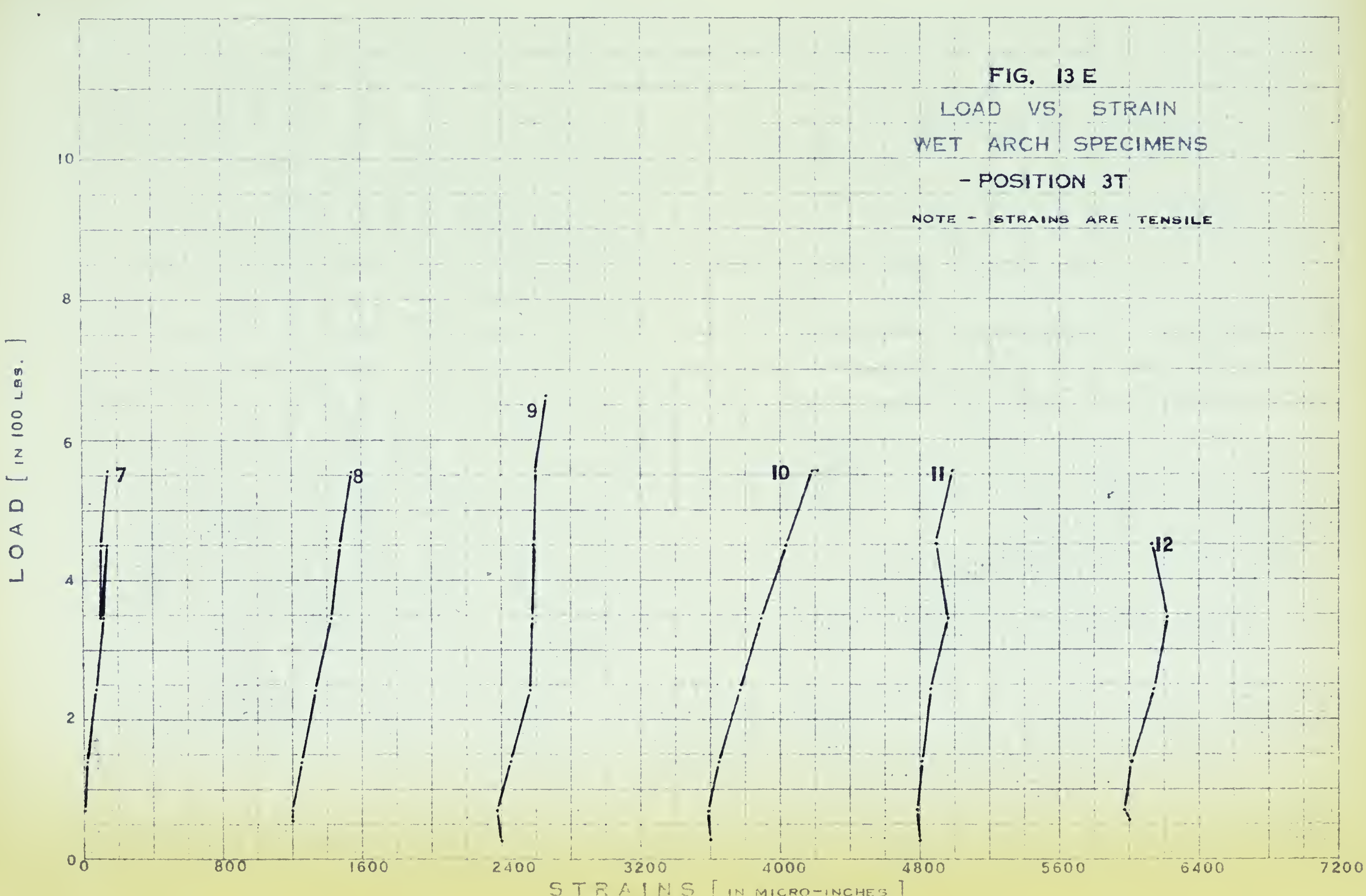


FIG. 13 E
LOAD VS. STRAIN
WET ARCH SPECIMENS
- POSITION 3T
NOTE - STRAINS ARE TENSILE
7
8
9
10
11
12
0
2
4
6
8
10
LOAD [IN 100 LBS.]
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]

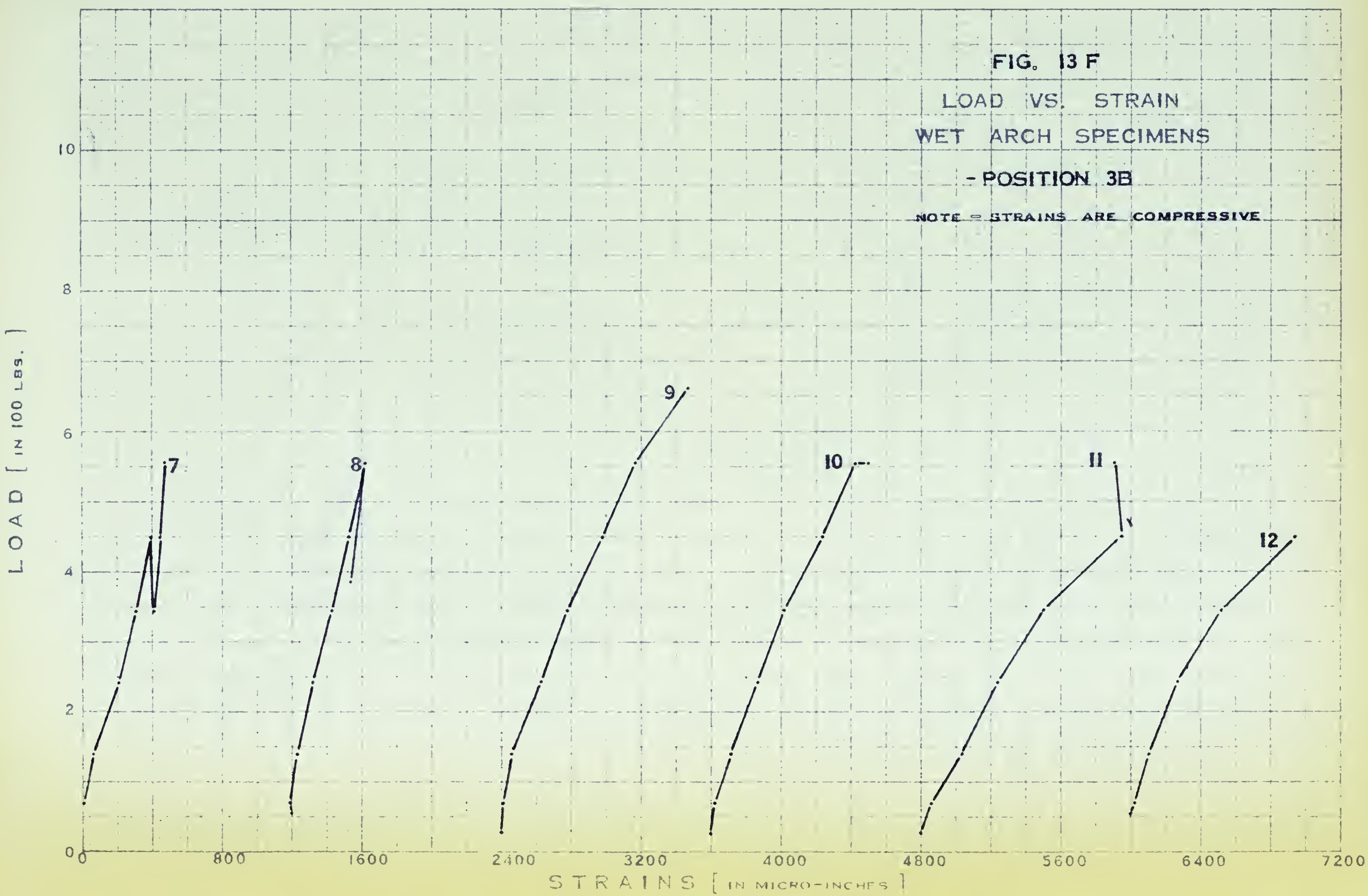


FIG. 13 F

LOAD VS. STRAIN

WET ARCH SPECIMENS

- POSITION 3B

NOTE = STRAINS ARE COMPRESSIVE

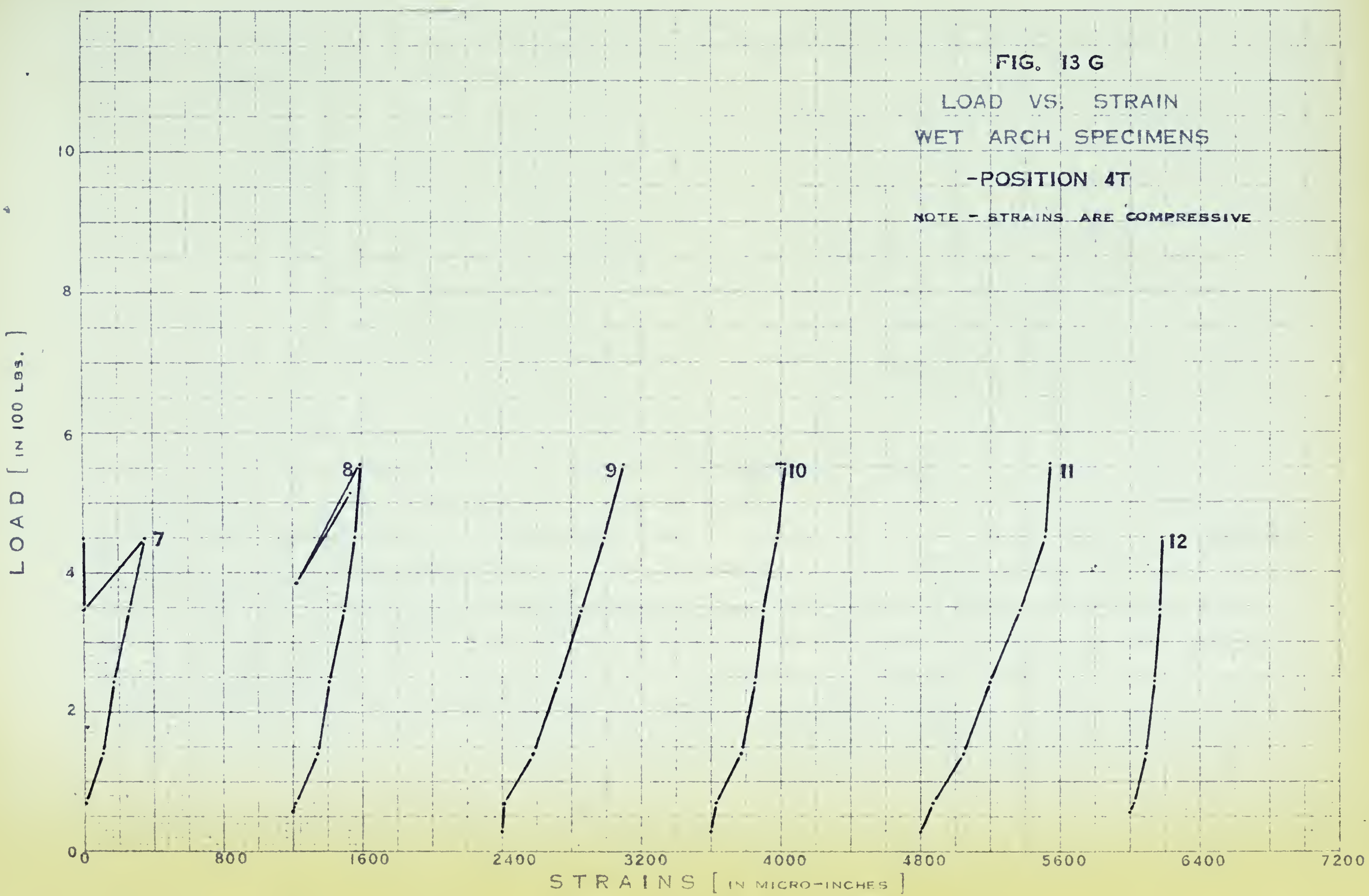


FIG. 13 G
LOAD VS. STRAIN
WET ARCH SPECIMENS
-POSITION 4T
NOTE - STRAINS ARE COMPRESSIVE
LOAD [IN 100 LBS.]
STRAINS [IN MICRO-INCHES]
0
2
4
6
8
10
800
1600
2400
3200
4000
4800
5600
6400
7200
7
8
9
10
11
12

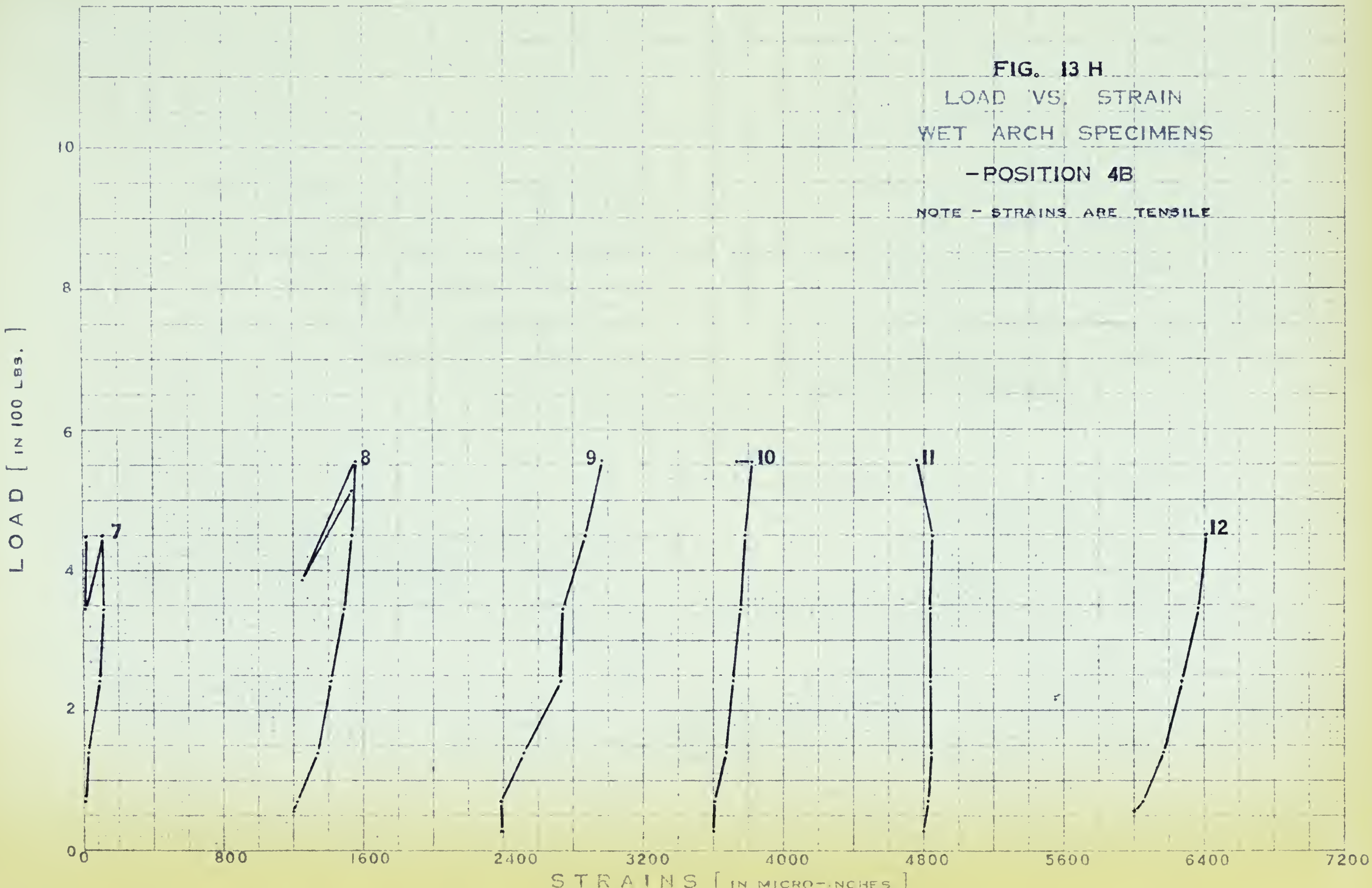


FIG. 13 H
LOAD VS. STRAIN
WET ARCH SPECIMENS
-POSITION 4B
NOTE - STRAINS ARE TENSILE
7
8
9
10
11
12
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
2
4
6
8
10
LOAD [IN 100 LBS.]

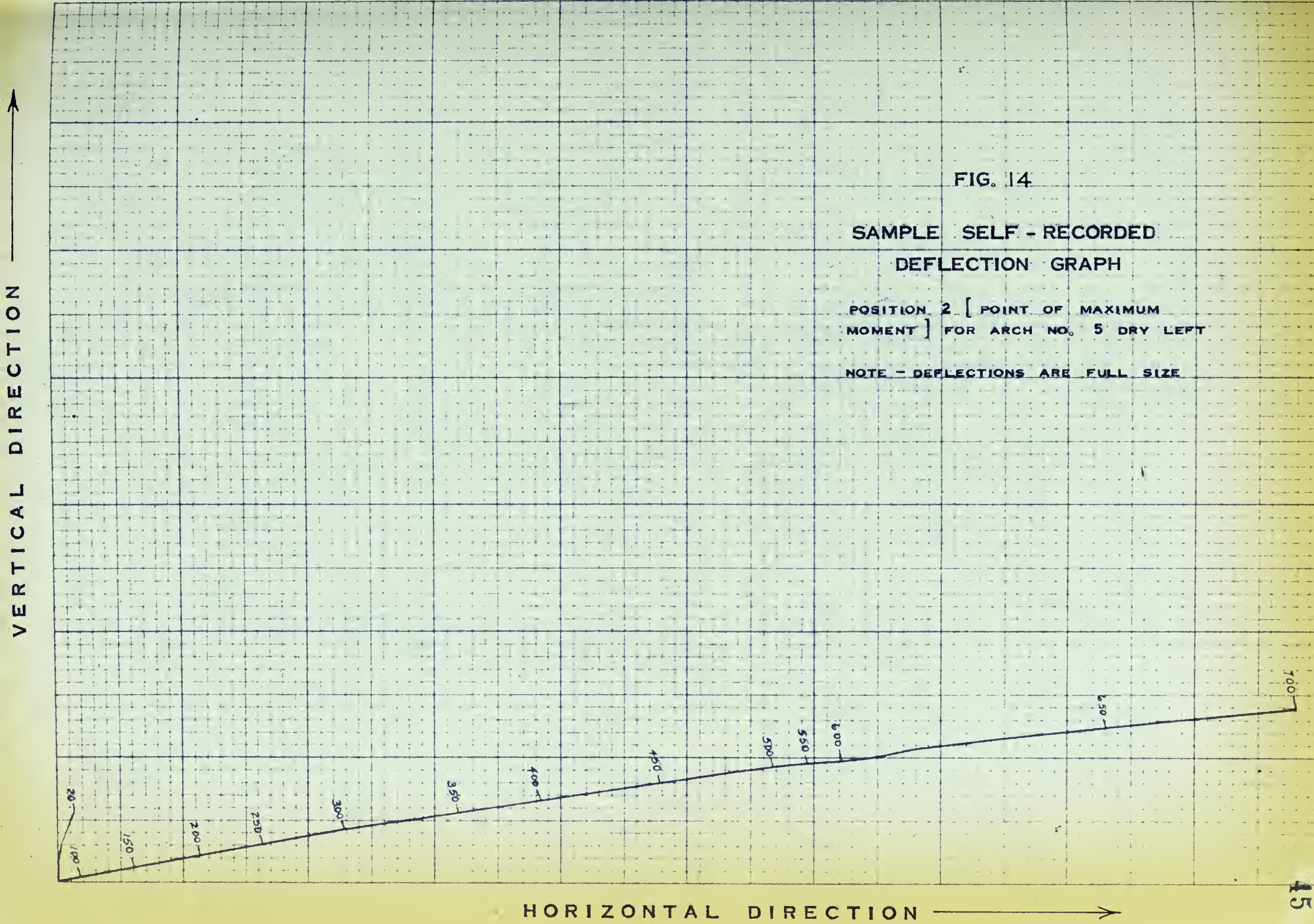


FIG. 14

SAMPLE SELF - RECORDED DEFLECTION GRAPH

POSITION 2 [POINT OF MAXIMUM MOMENT] FOR ARCH NO. 5 DRY LEFT

NOTE – DEFLECTIONS ARE FULL SIZE

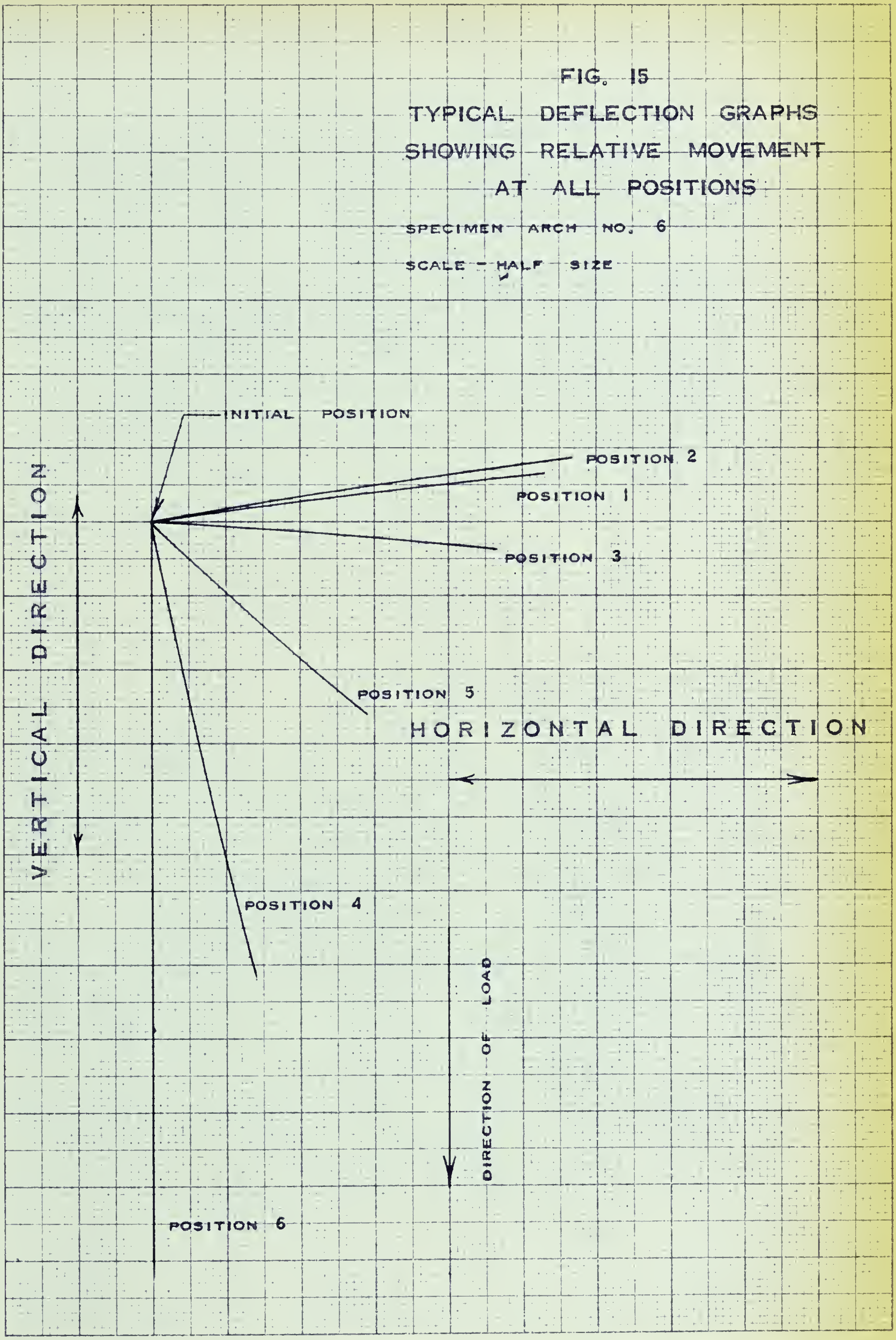


FIG. 15
TYPICAL DEFLECTION GRAPHS
SHOWING RELATIVE MOVEMENT
AT ALL POSITIONS

SPECIMEN ARCH NO. 6

SCALE - HALF SIZE

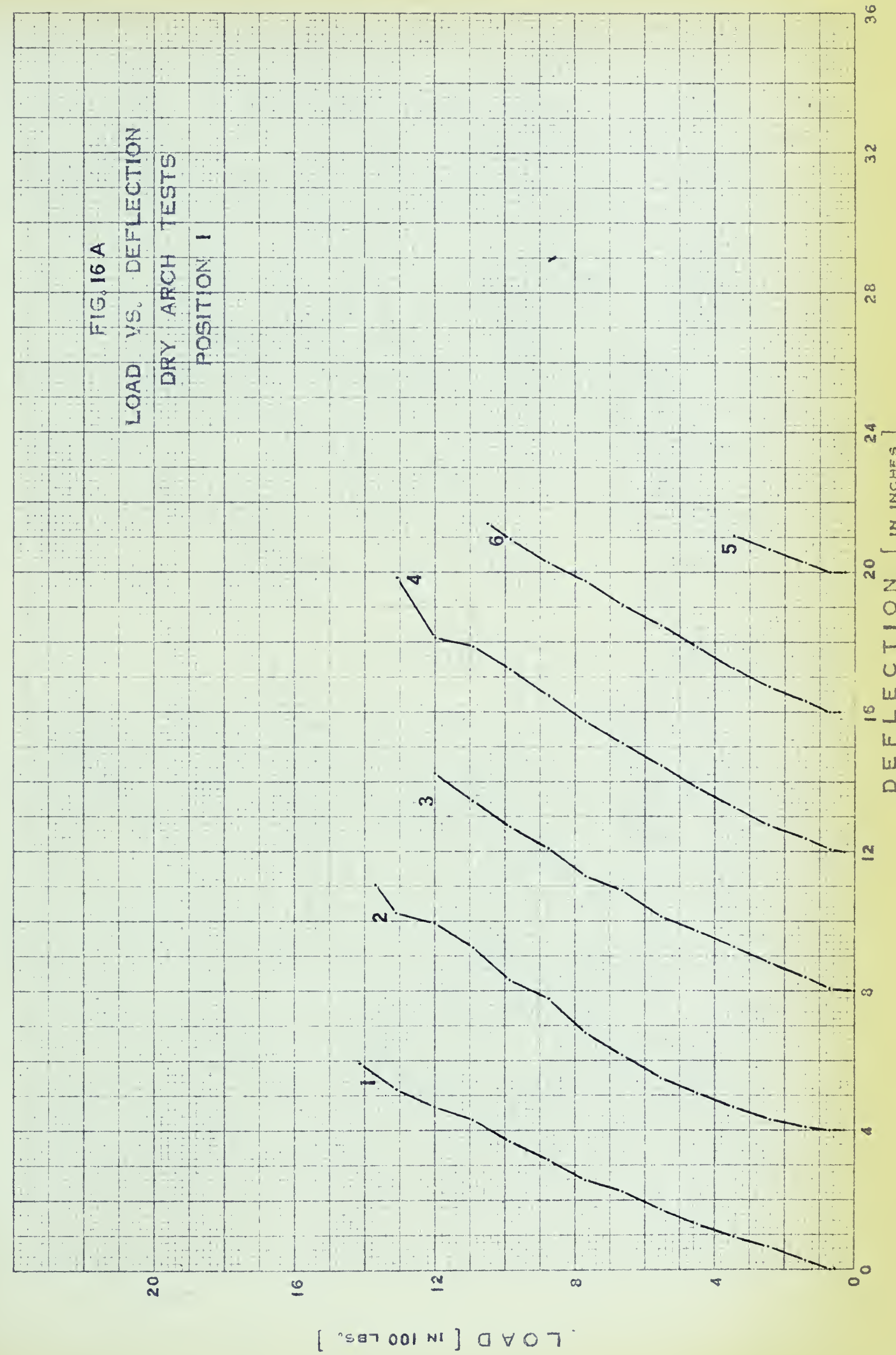


FIG. 16 A
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION I
1
2
3
4
5
6
0
4
8
12
16
20
24
28
32
36
DEFLECTION [IN INCHES]
LOAD [IN 100 LBS.]

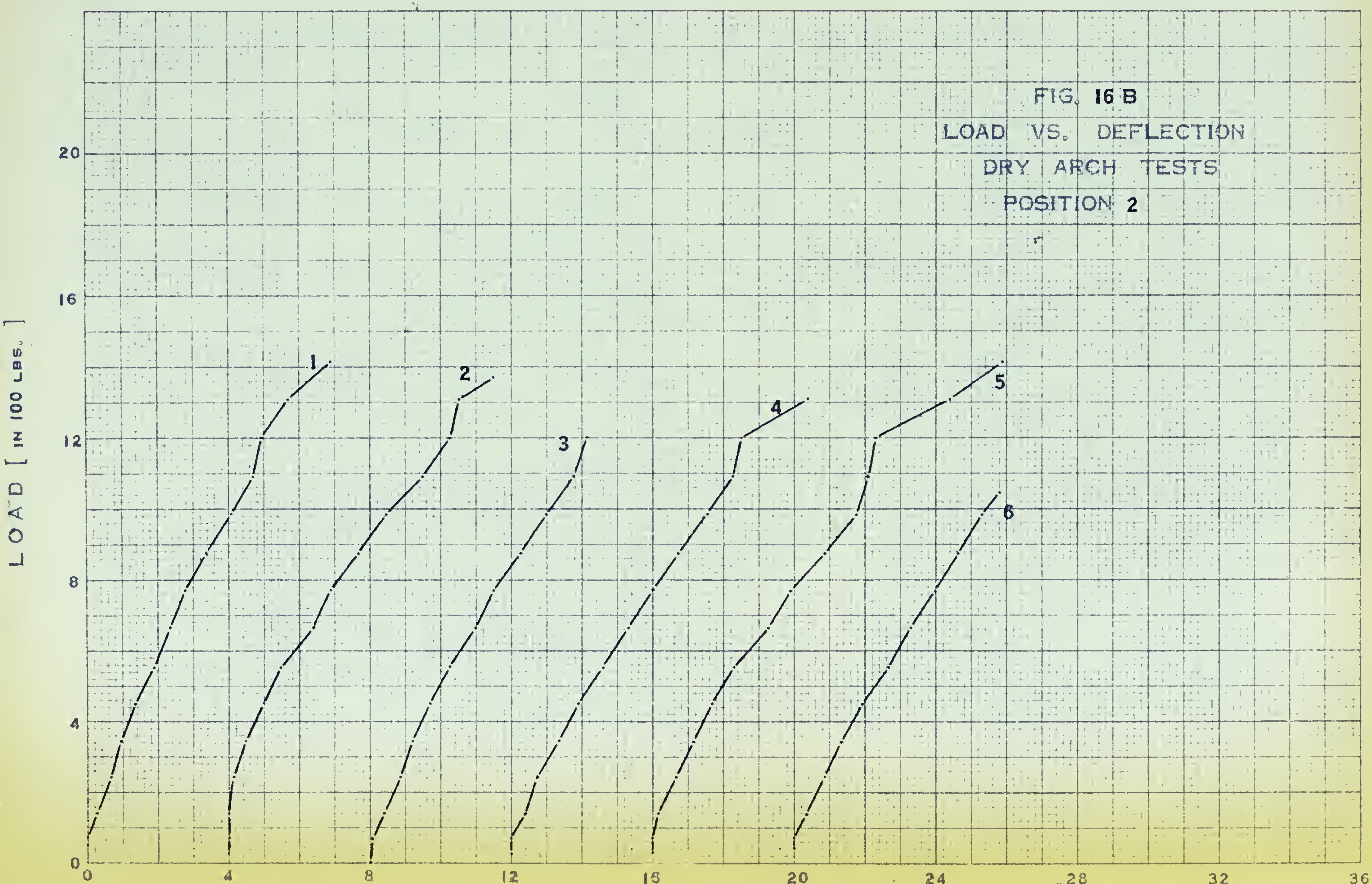


FIG. 16 B
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION 2

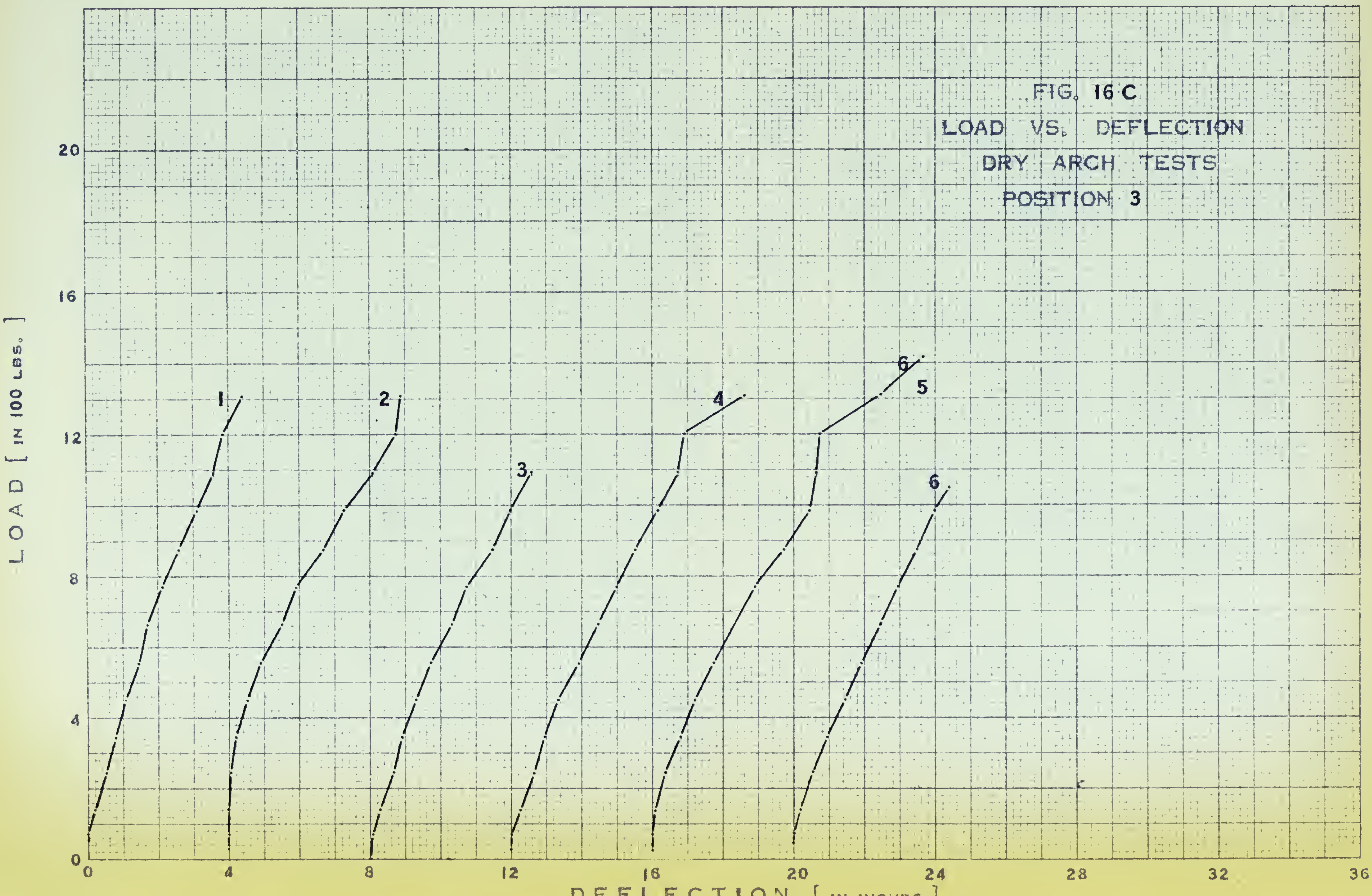


FIG. 16 C
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION 3

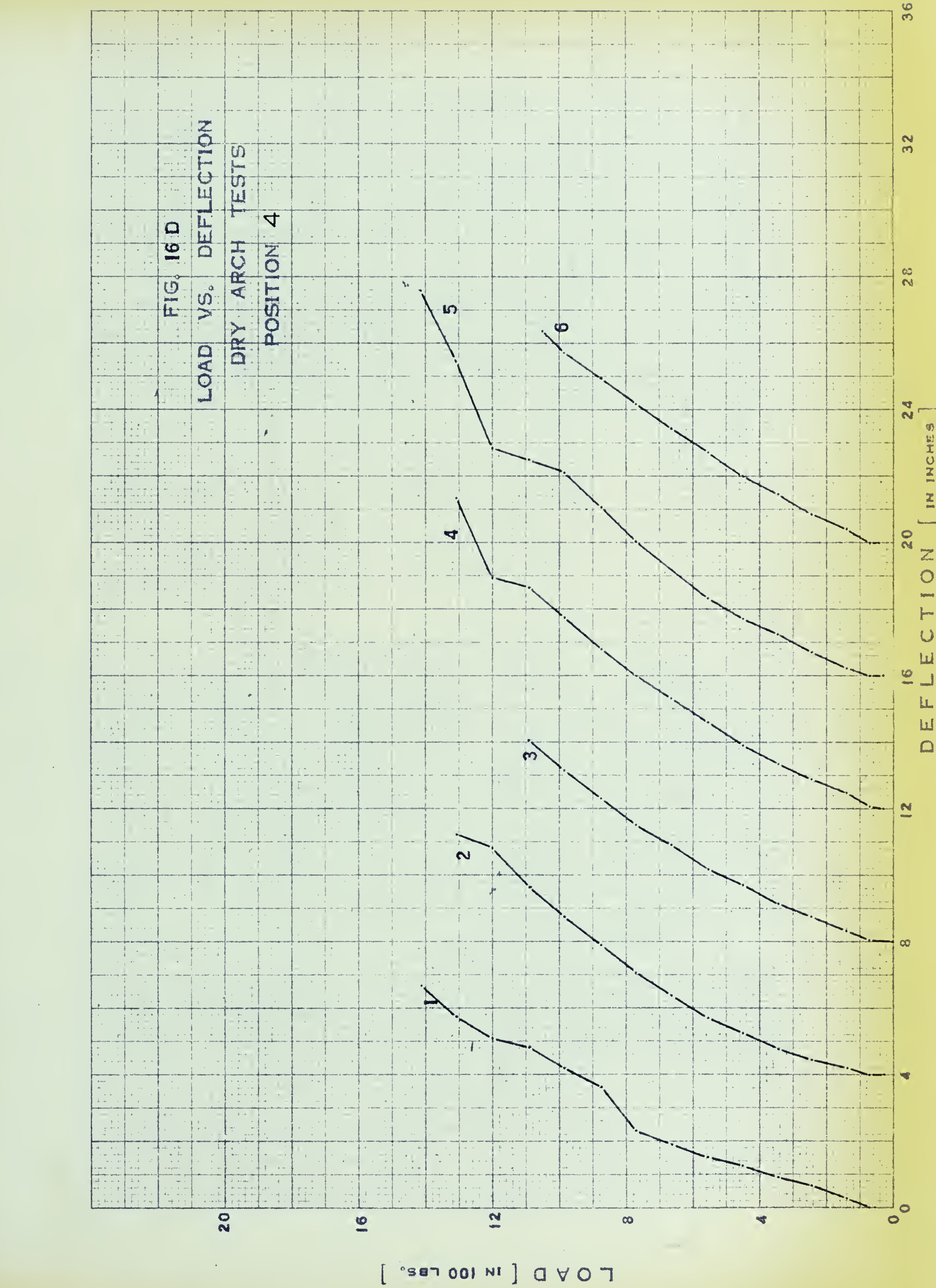


FIG. 16 D
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION 4
1
2
3
4
5
6
0
4
8
12
16
20
24
28
32
36
DEFLECTION [IN INCHES]
LOAD [IN 100 LBS.]

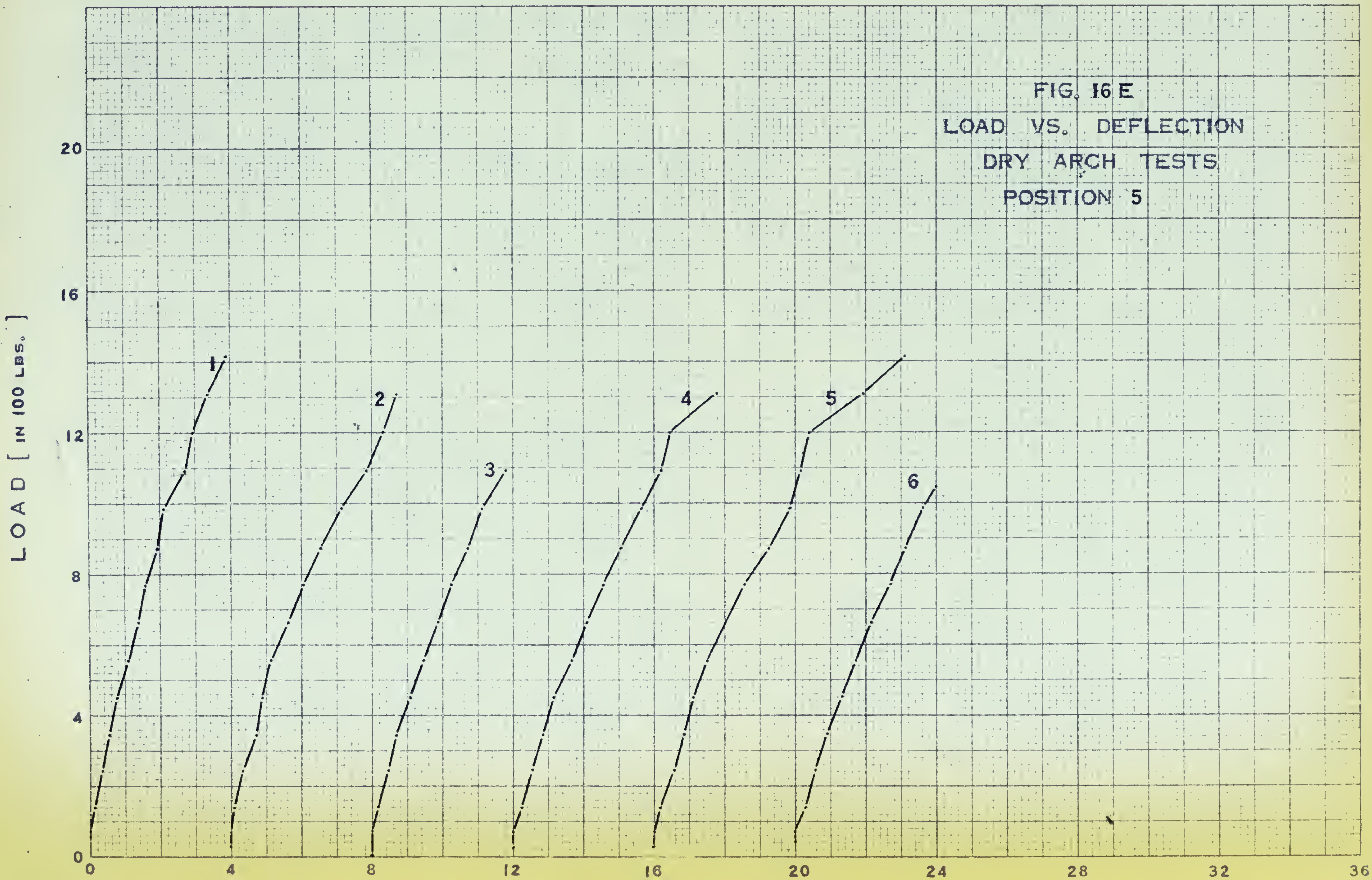


FIG. 16 E
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION 5
LOAD [IN 100 LBS.]
0
4
8
12
16
20
24
28
32
36
1
2
3
4
5
6

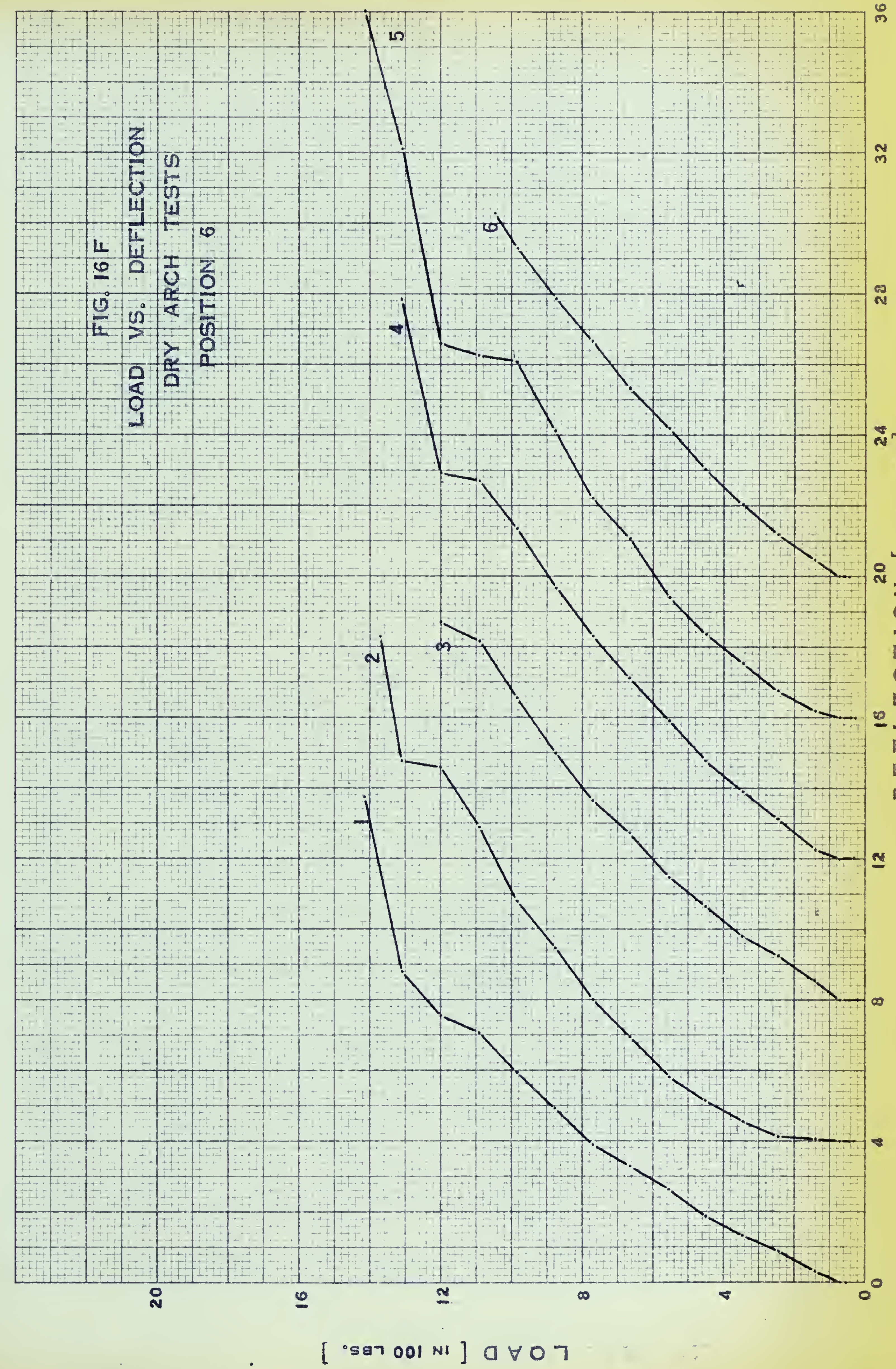


FIG. 16 F
LOAD VS. DEFLECTION
DRY ARCH TESTS
POSITION 6

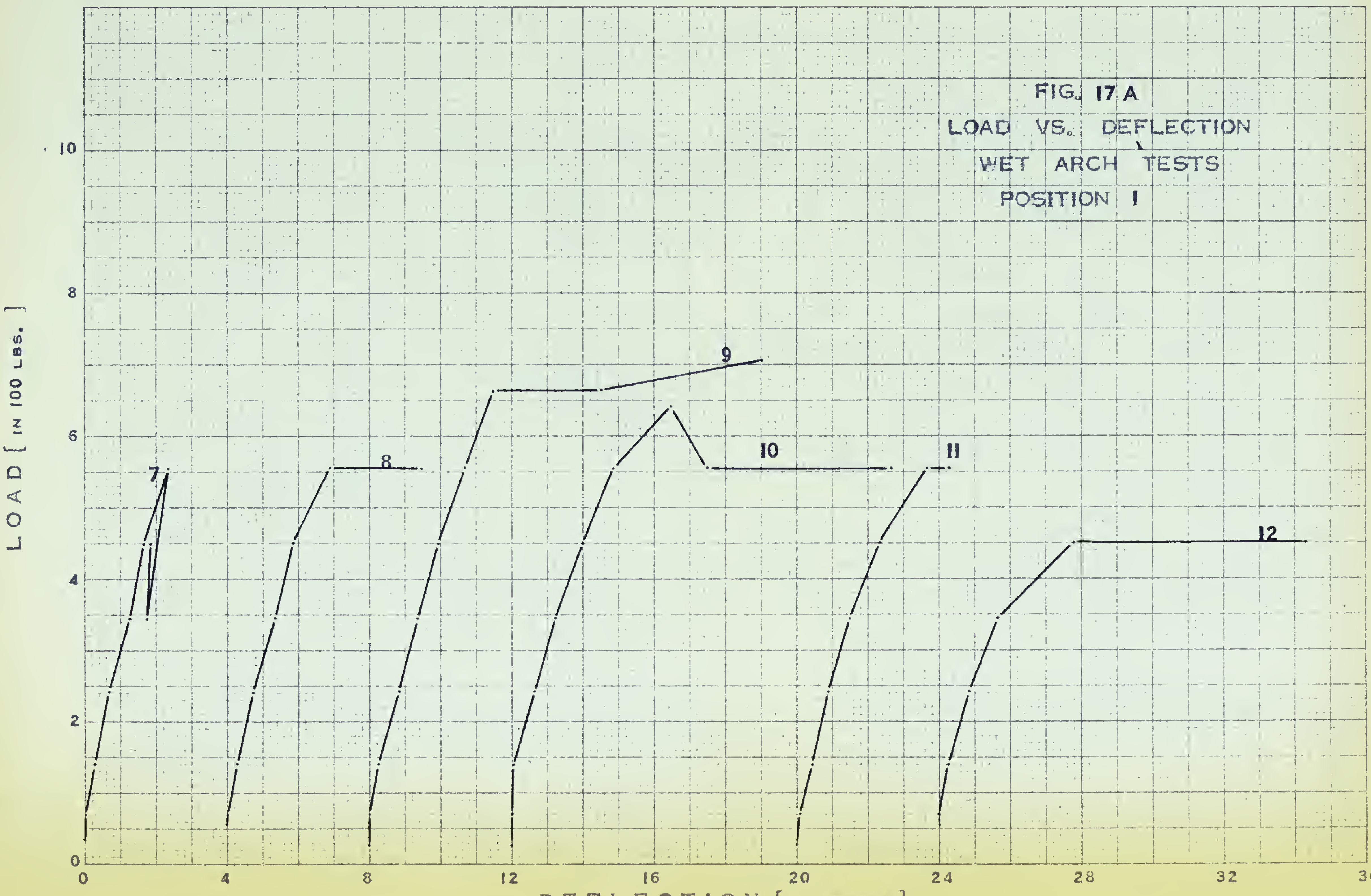


FIG. 17 A
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION I
7
8
9
10
11
12
LOAD [IN 100 LBS.]
0
2
4
6
8
10
DEFLECTION [IN INCHES]
0
4
8
12
16
20
24
28
32
36

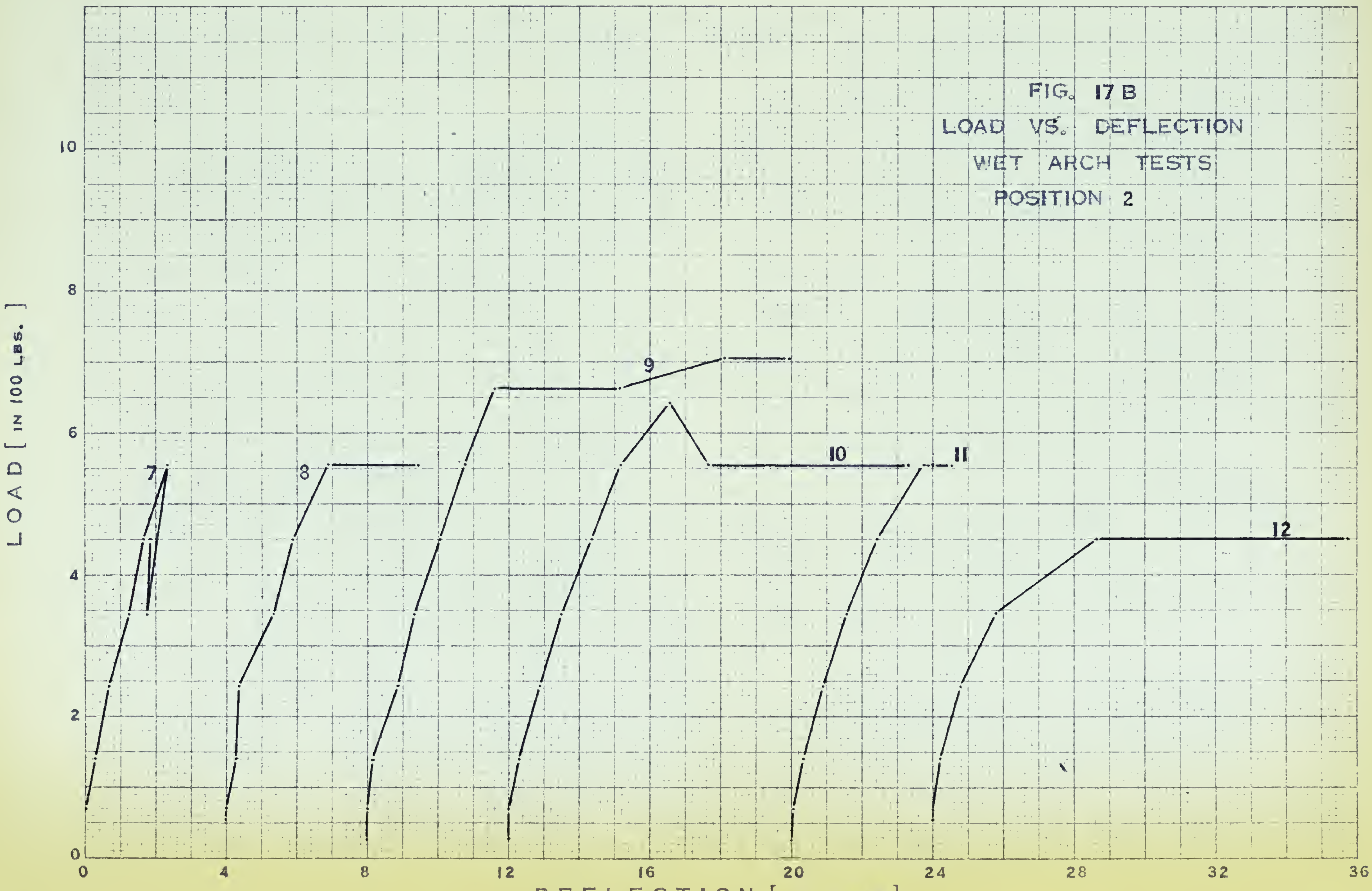


FIG. 17 B
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION 2
7
8
9
10
11
12
LOAD [IN 100 LBS.]
0
2
4
6
8
10
DEFLECTION [IN INCHES]
0
4
8
12
16
20
24
28
32
36

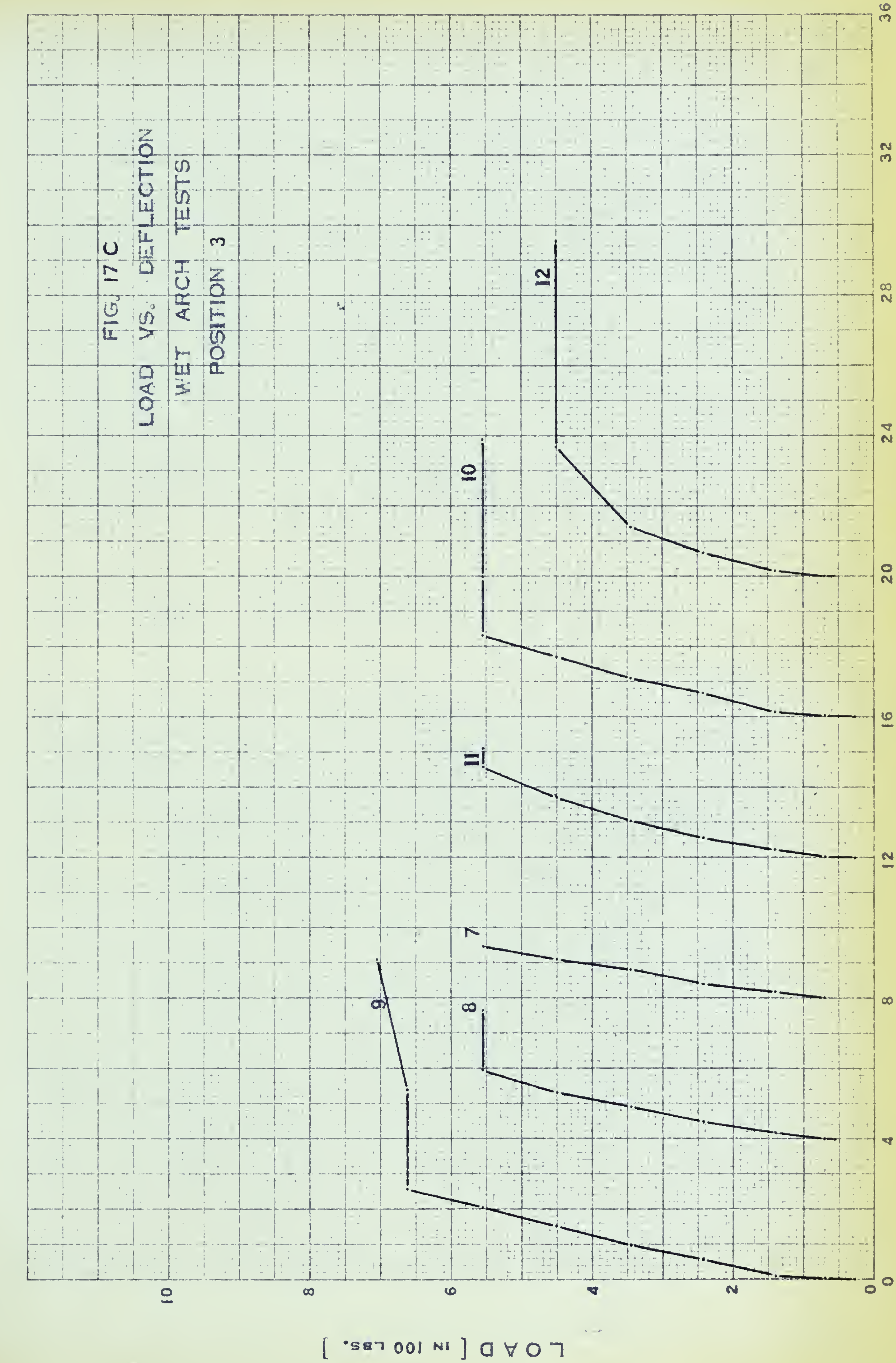


FIG. 17 C
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION 3

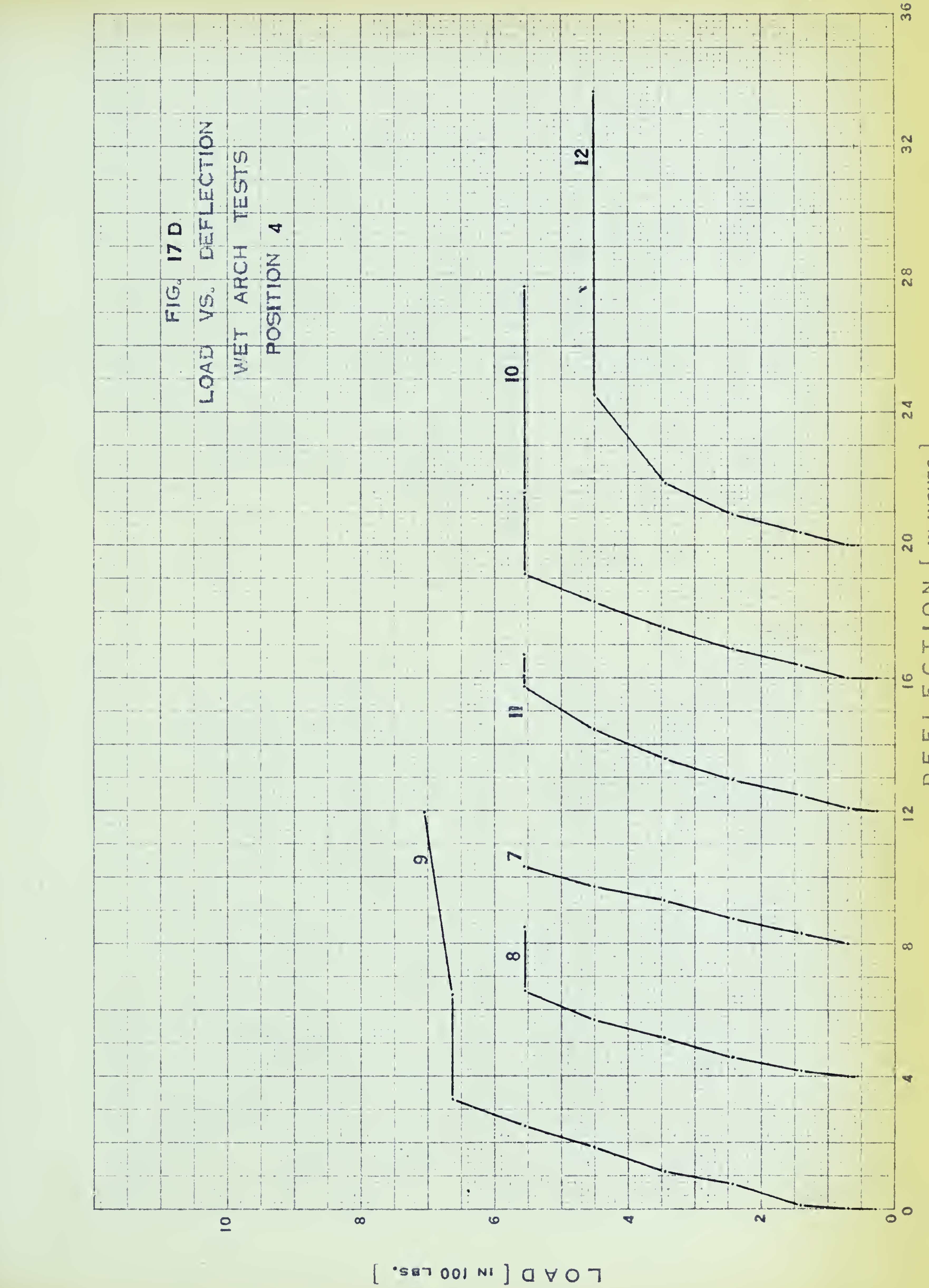


FIG. 17 D
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION 4
9
7
8
11
10
12
LOAD [IN 100 LBS.]
0
2
4
6
8
10
DEFLECTION [IN INCHES]
0
4
8
12
16
20
24
28
32
36

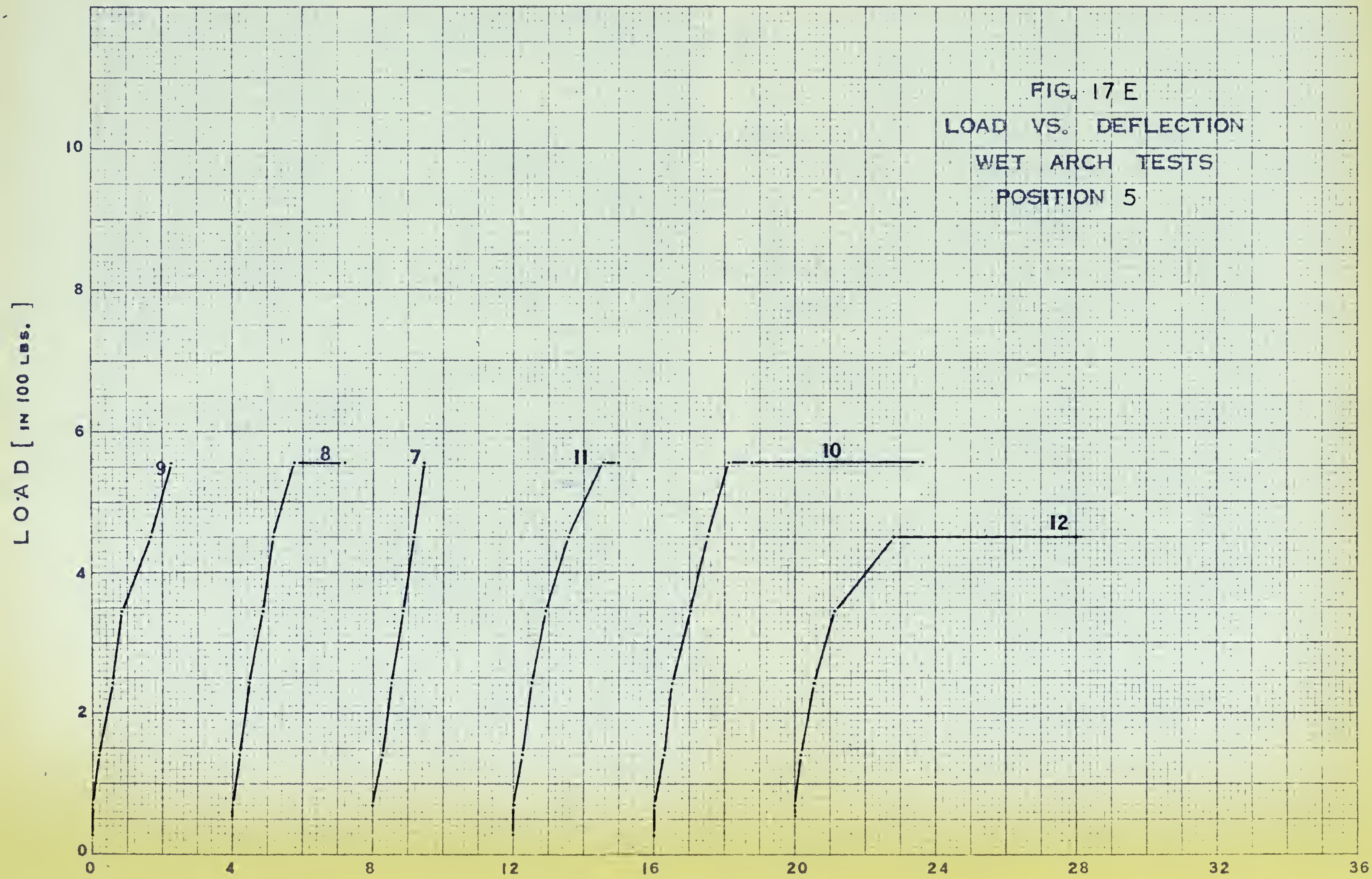


FIG. 17 E
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION 5
9
8
7
11
10
12
LOAD [IN 100 LBS.]
0
2
4
6
8
10
0
4
8
12
16
20
24
28
32
36
DEFLECTION [ ]

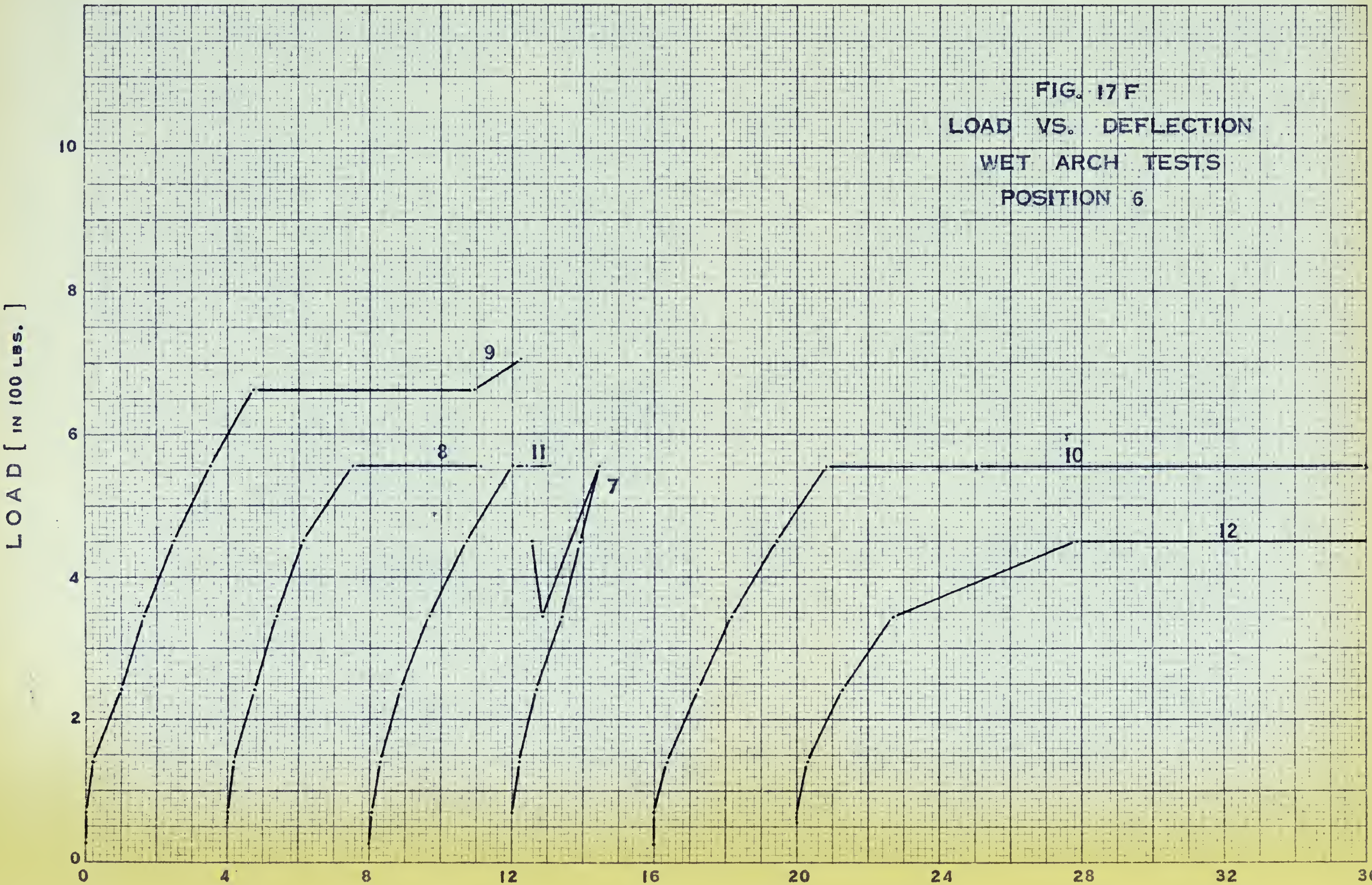


FIG. 17 F
LOAD VS. DEFLECTION
WET ARCH TESTS
POSITION 6
LOAD [IN 100 LBS.]
0
2
4
6
8
10
0
4
8
12
16
20
24
28
32
36
9
8
11
7
10
12

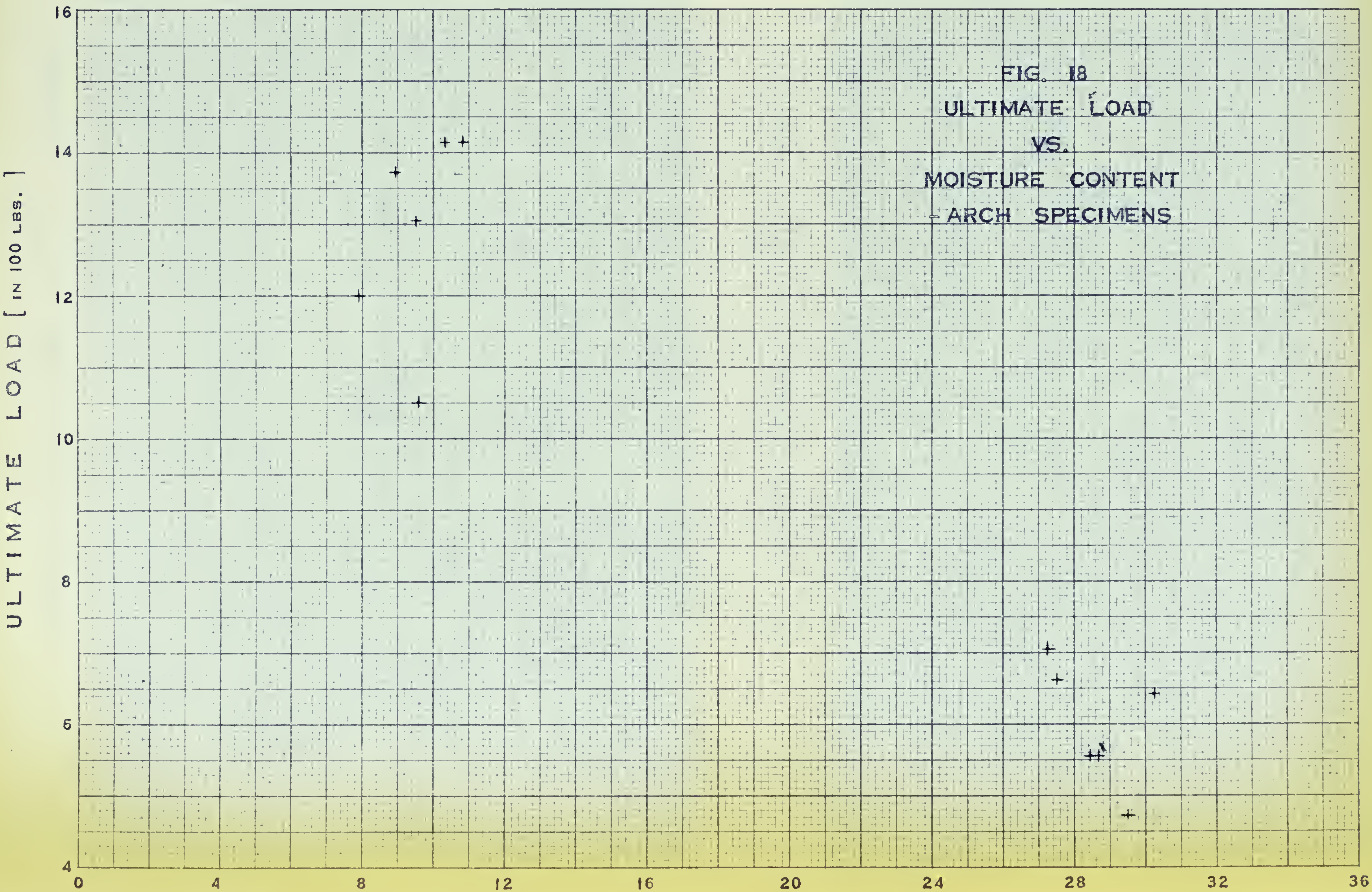


FIG. 18
ULTIMATE LOAD
VS.
MOISTURE CONTENT
- ARCH SPECIMENS
ULTIMATE LOAD [IN 100 LBS.]
16
14
12
10
8
6
4
0
4
8
12
16
20
24
28
32
36

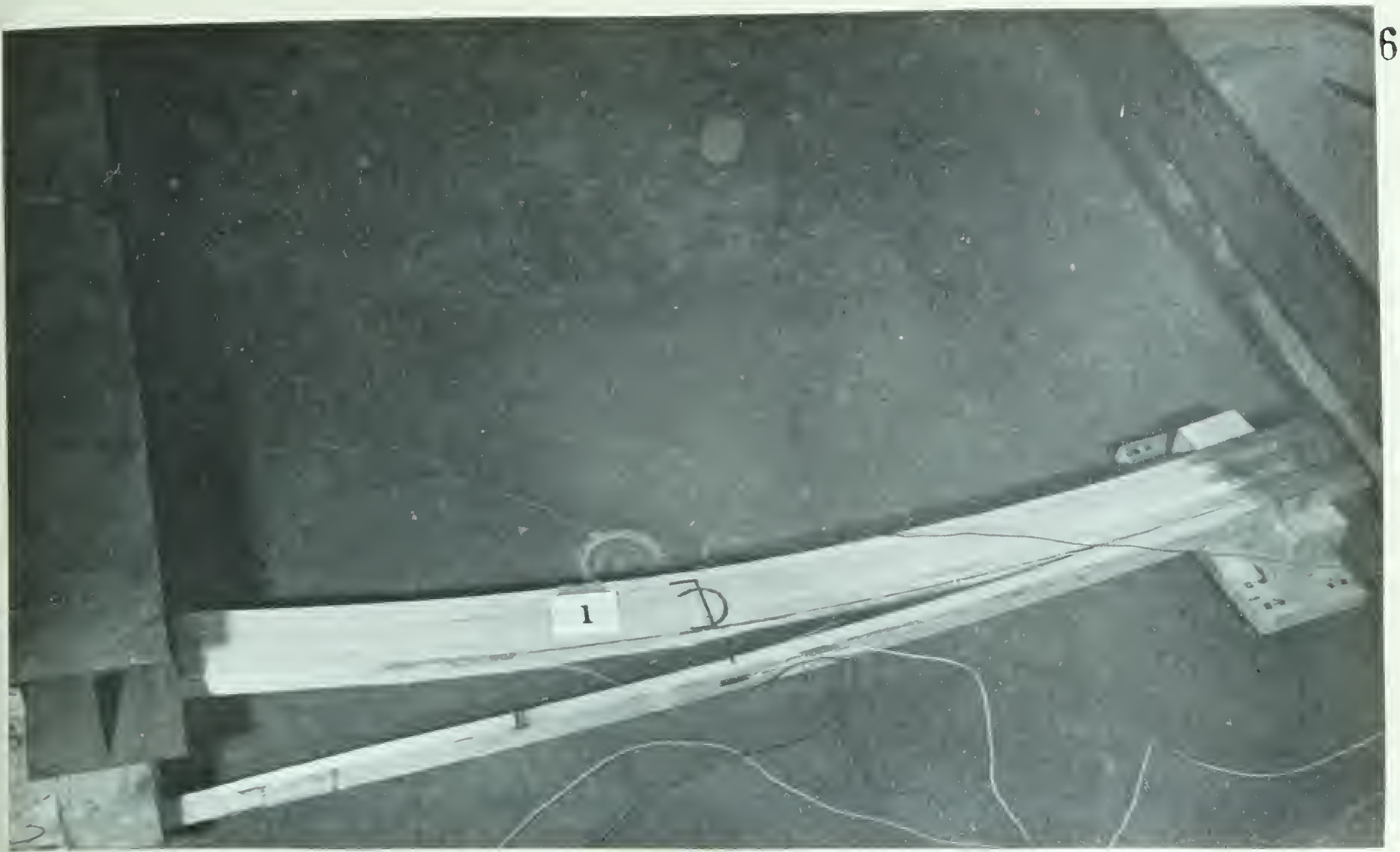


FIGURE 19. - View of Failure in Arch Specimen No. 1.

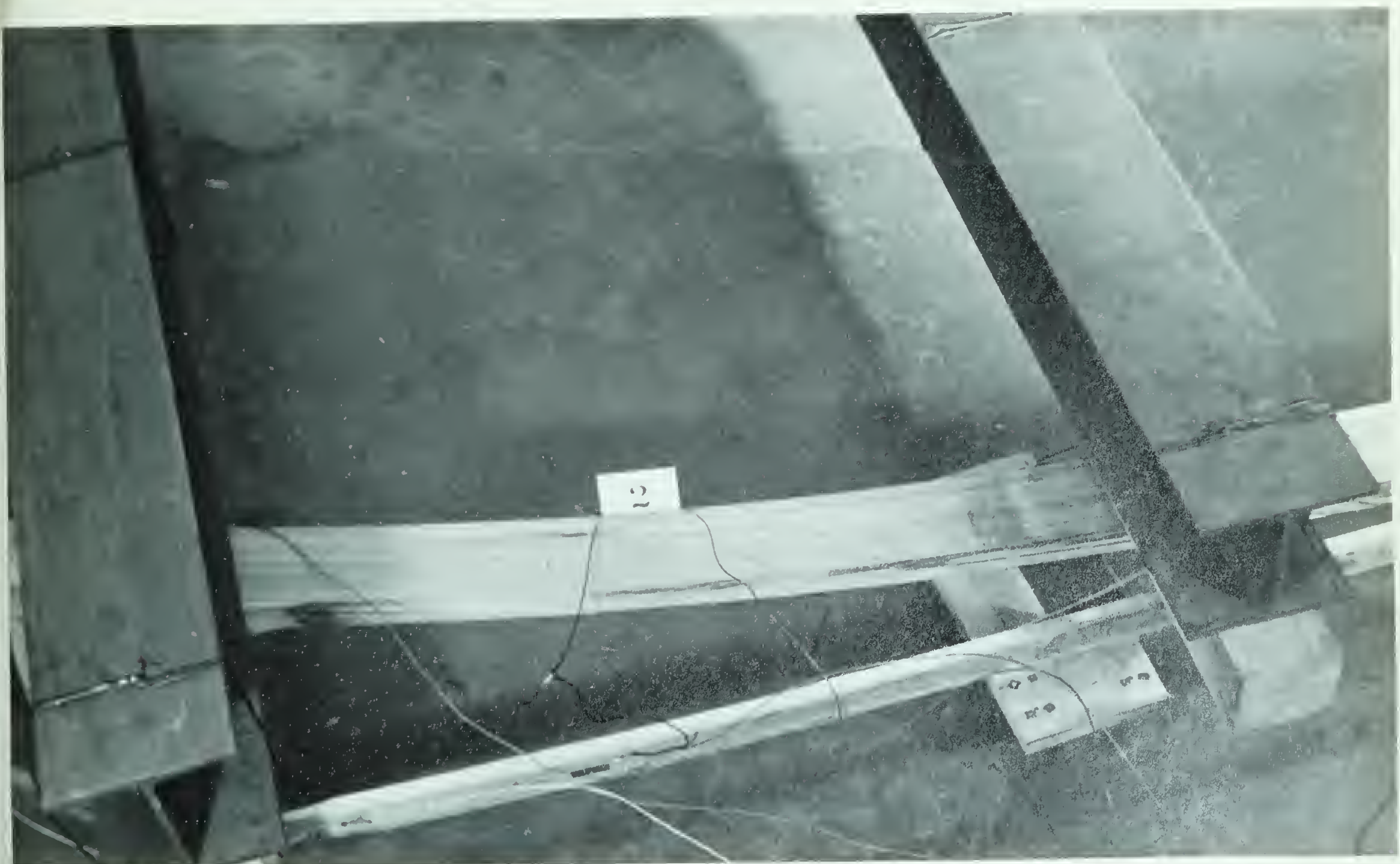


FIGURE 20. - View of Failure in Arch Specimen No. 2.

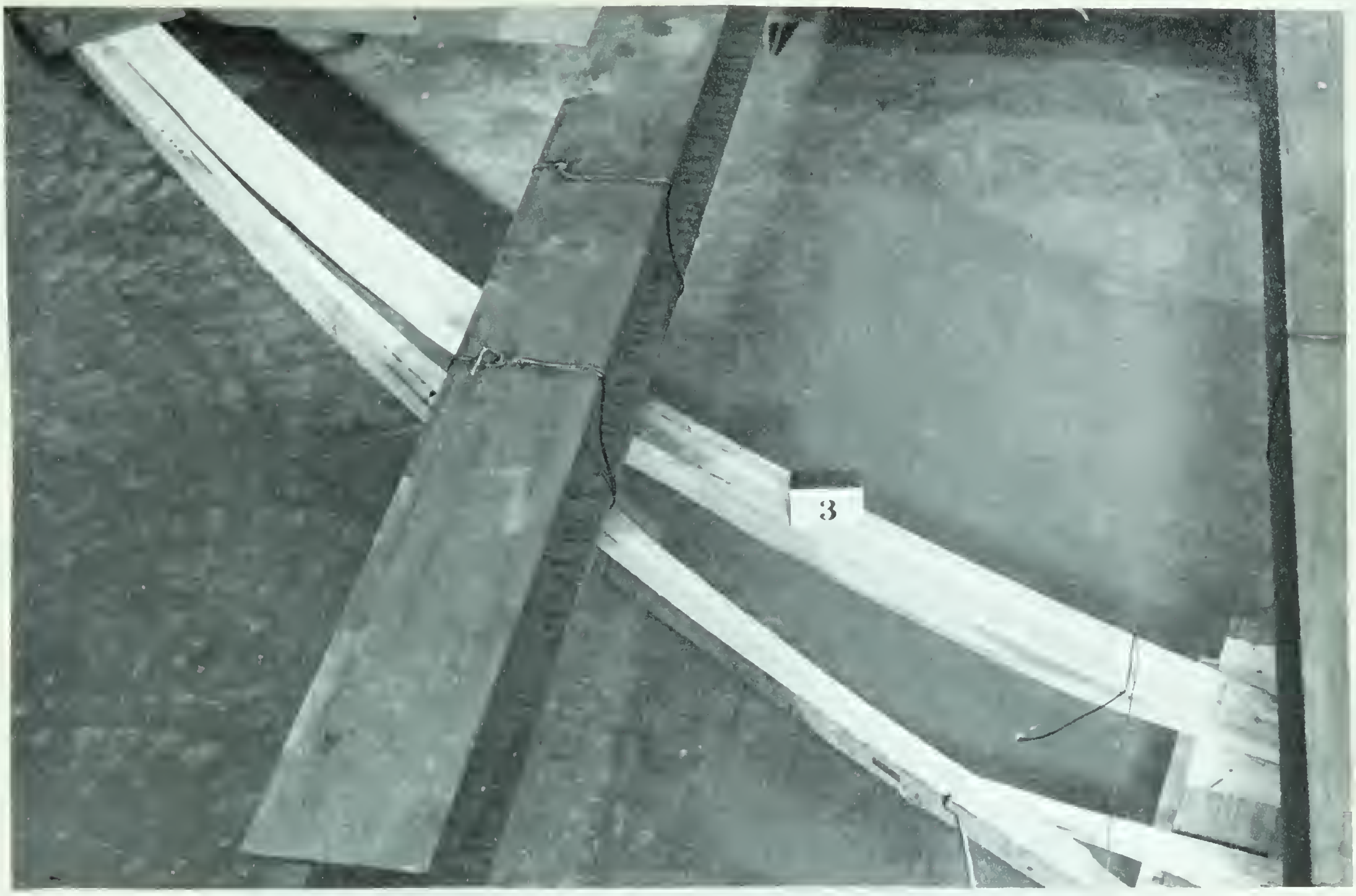


FIGURE 21. - View of Failure in Arch Specimen No. 3.

FIGURE 22. - View of Failure in Arch Specimen No. 5.

FIGURE 23. - View of Failure in Arch Specimen No. 6.

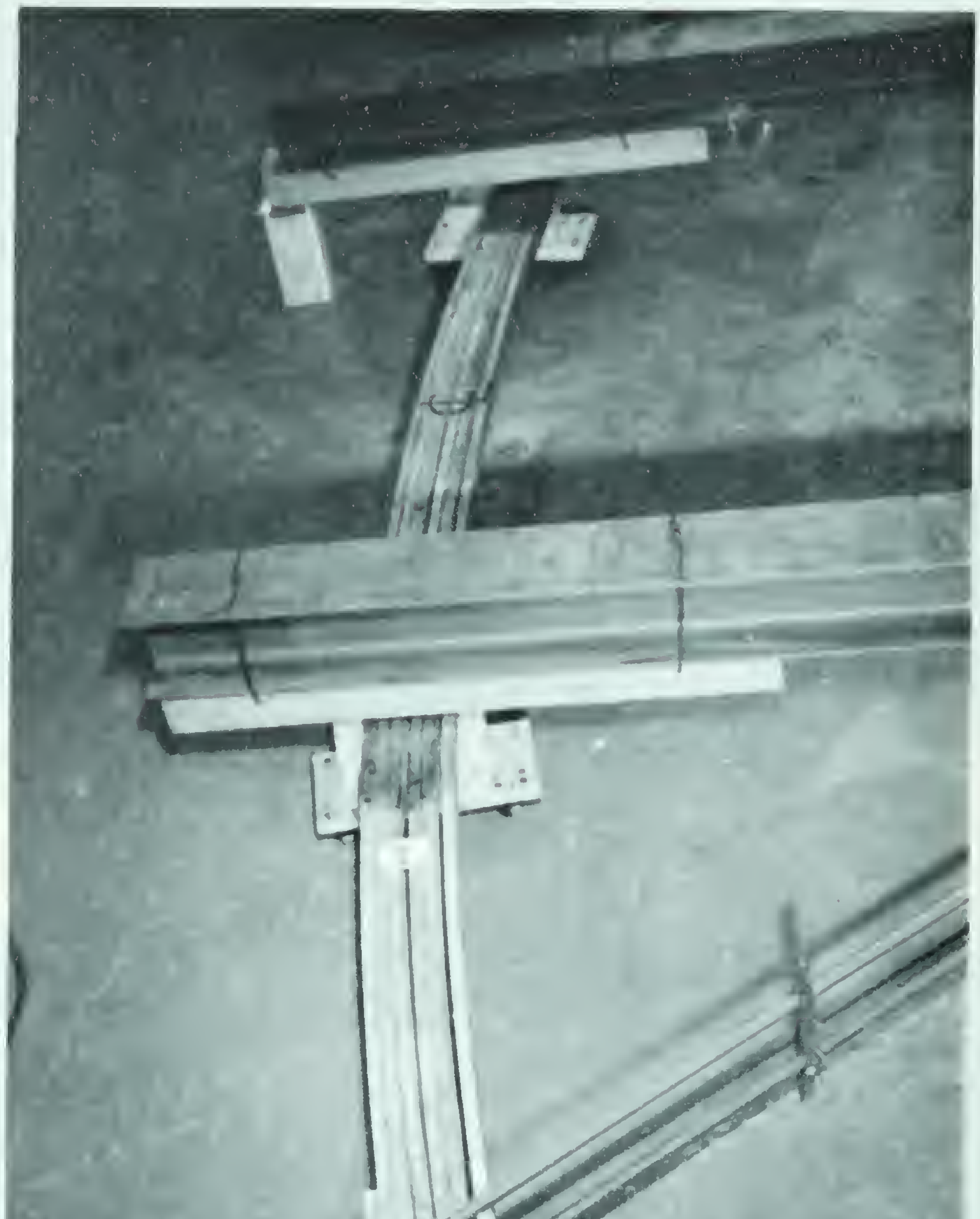


FIGURE 24. - View of Failure in Arch Specimen No. 7.

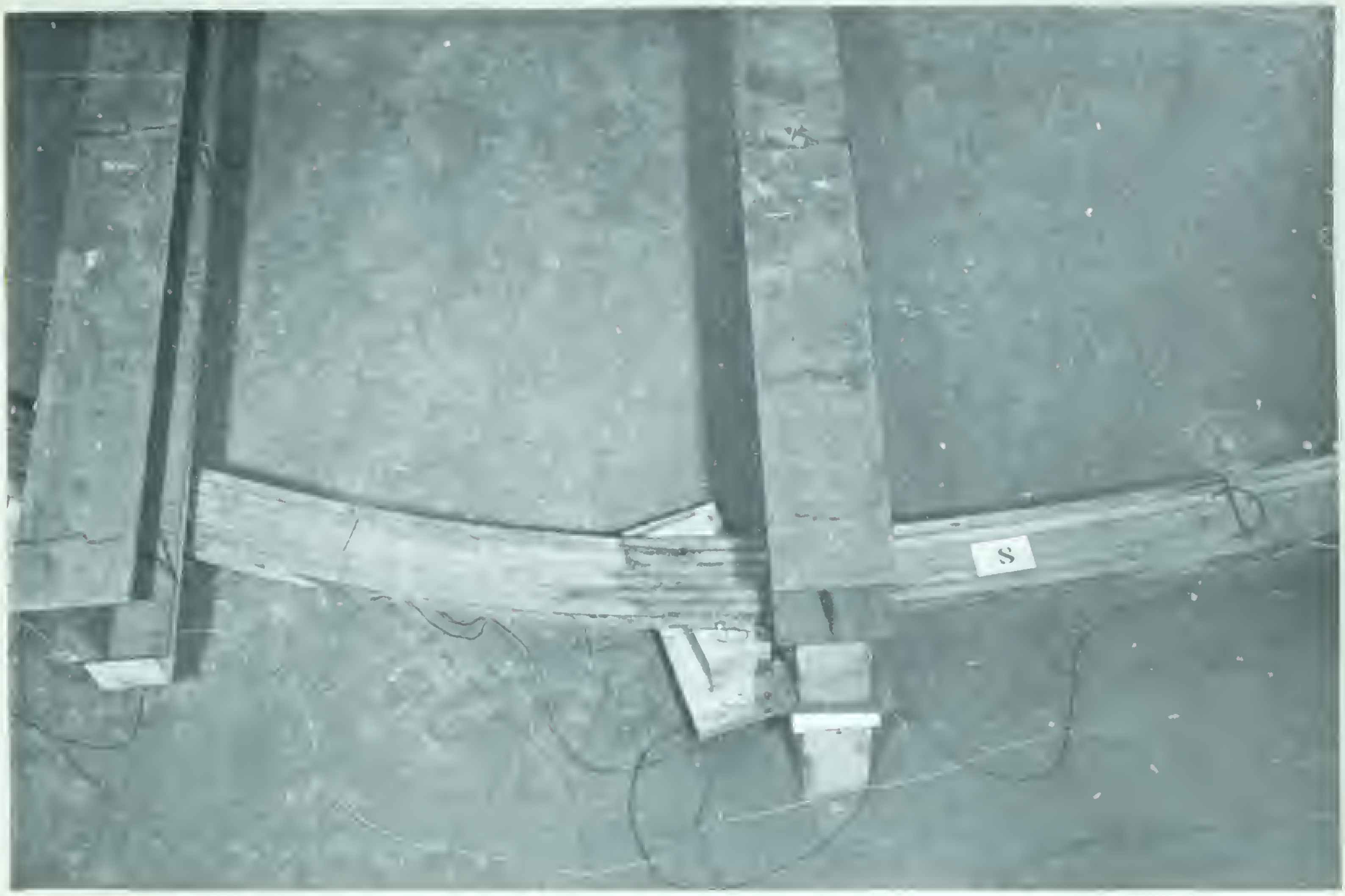


FIGURE 25. - View of Failure in Arch Specimen No. 8.

FIGURE 26. - View of Failure in Arch Specimen No. 9.

FIGURE 27. - View of Failure in Arch Specimen No. 10.

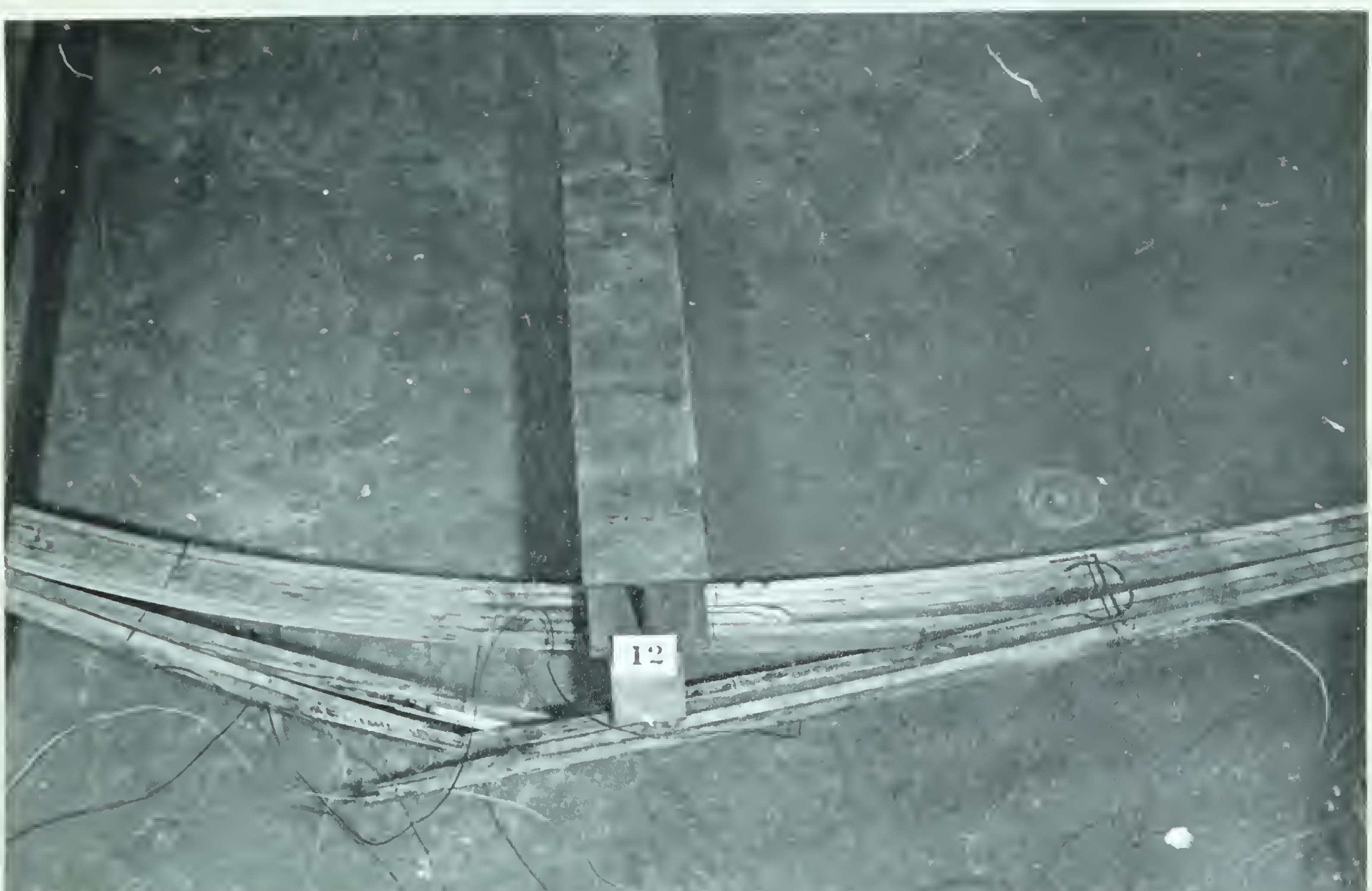


FIGURE 28. - View of Failure in Arch Specimen No. 12.

FIGURE 29. - View of Failure in Arch Specimen No. 11.

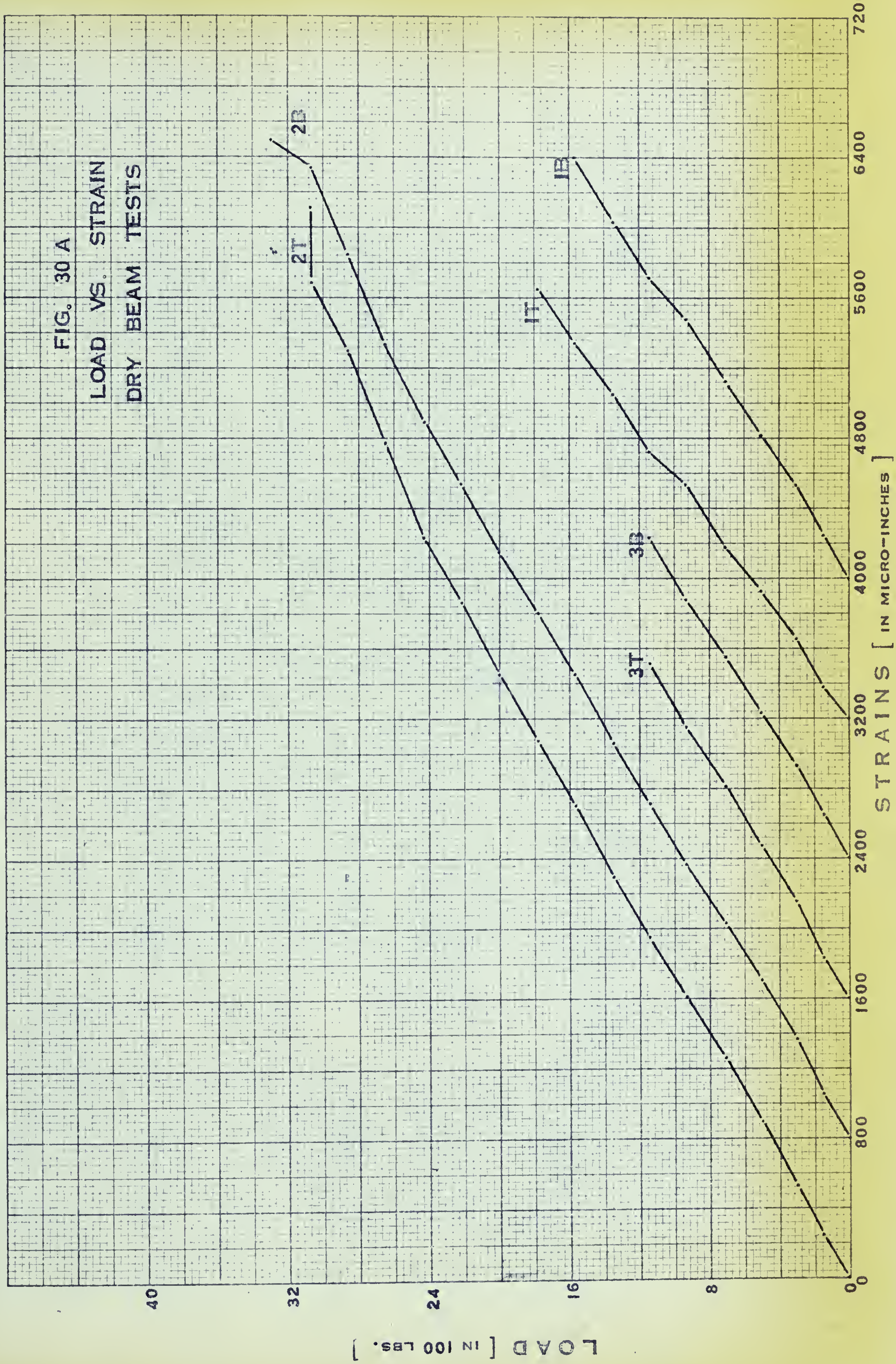


FIG. 30 A
LOAD VS. STRAIN
DRY BEAM TESTS
2B
2T
IT
IB
3B
3T
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
8
16
24
32
40
LOAD [IN 100 LBS.]

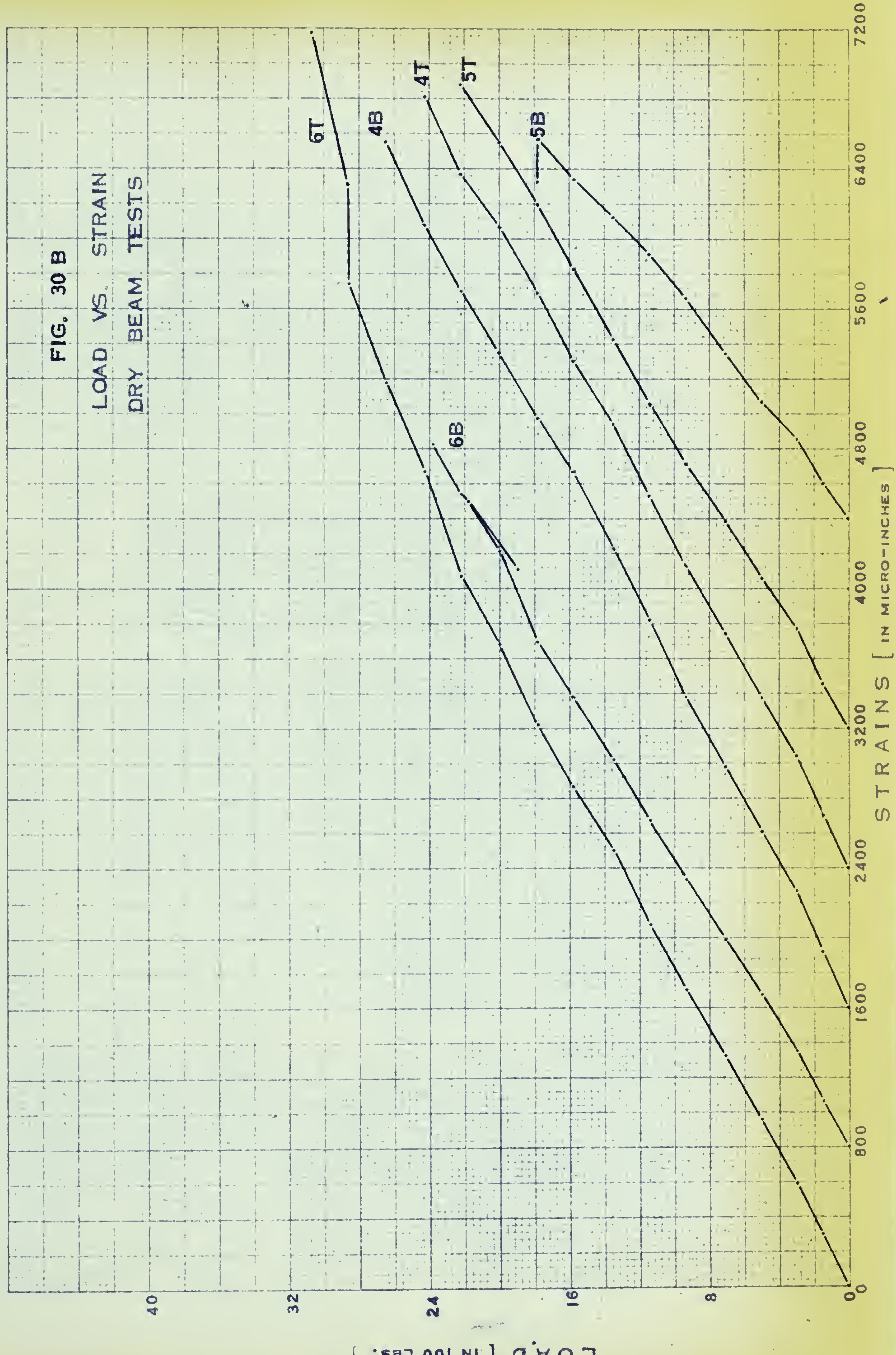


FIG. 30 B
LOAD VS. STRAIN
DRY BEAM TESTS
6T
4B
4T
5T
5B
6B
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
8
16
24
32
40
LOAD [IN 100 LBS.]

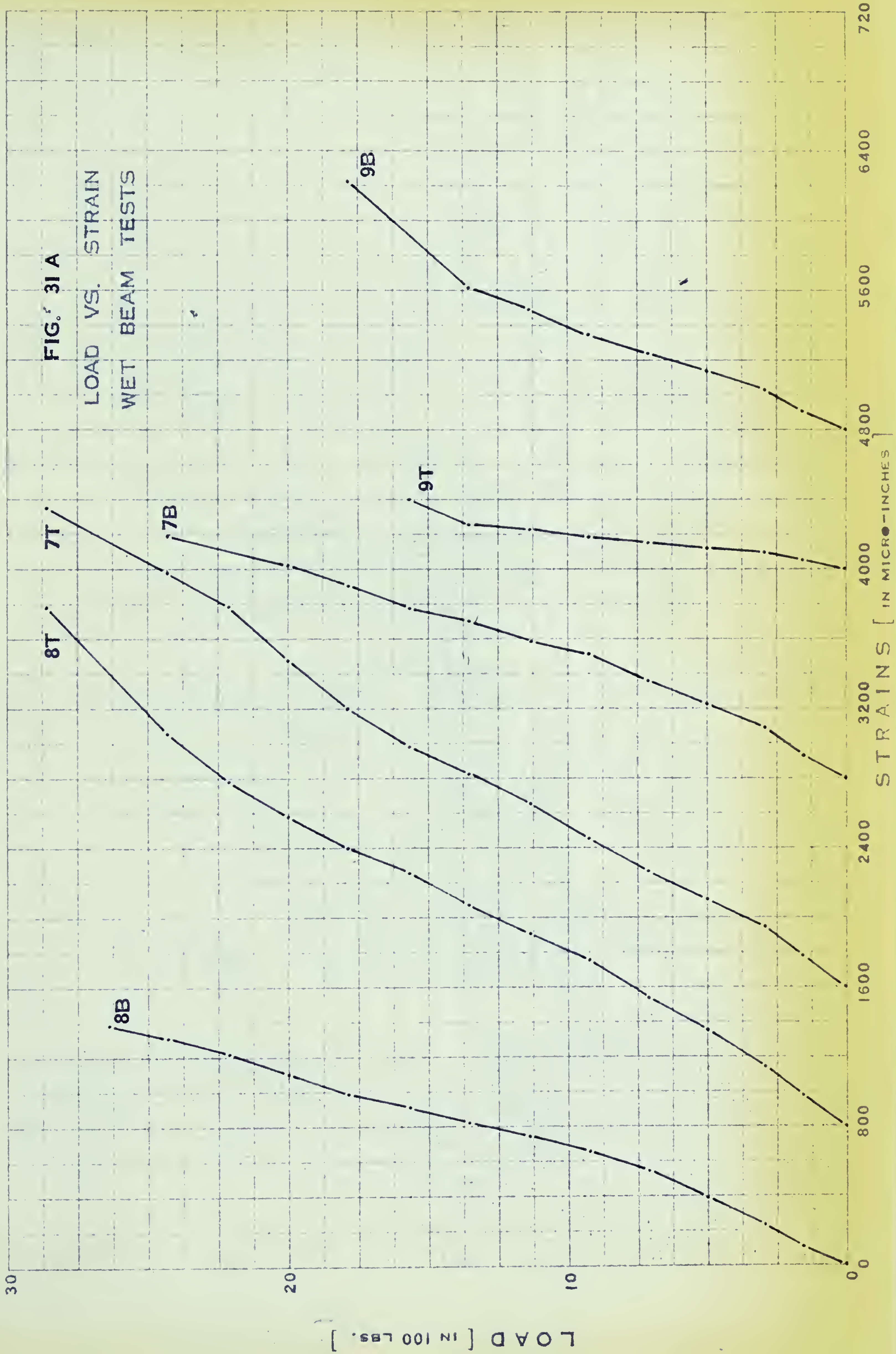


FIG. 31 A
LOAD VS. STRAIN
WET BEAM TESTS

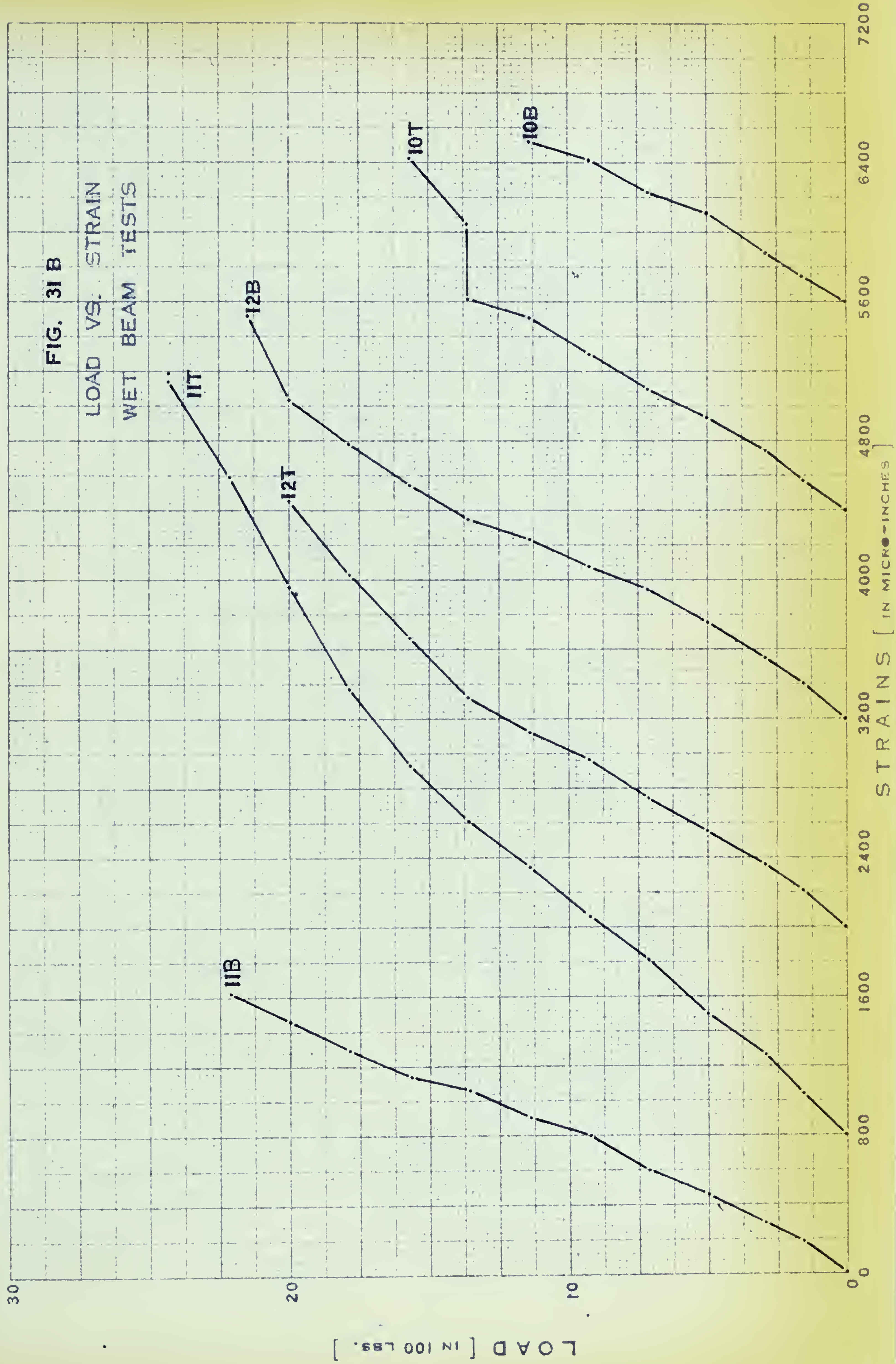


FIG. 31 B
LOAD VS. STRAIN
WET BEAM TESTS
10T
10B
11T
11B
12T
12B
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
10
20
30
LOAD [IN 100 LBS.]

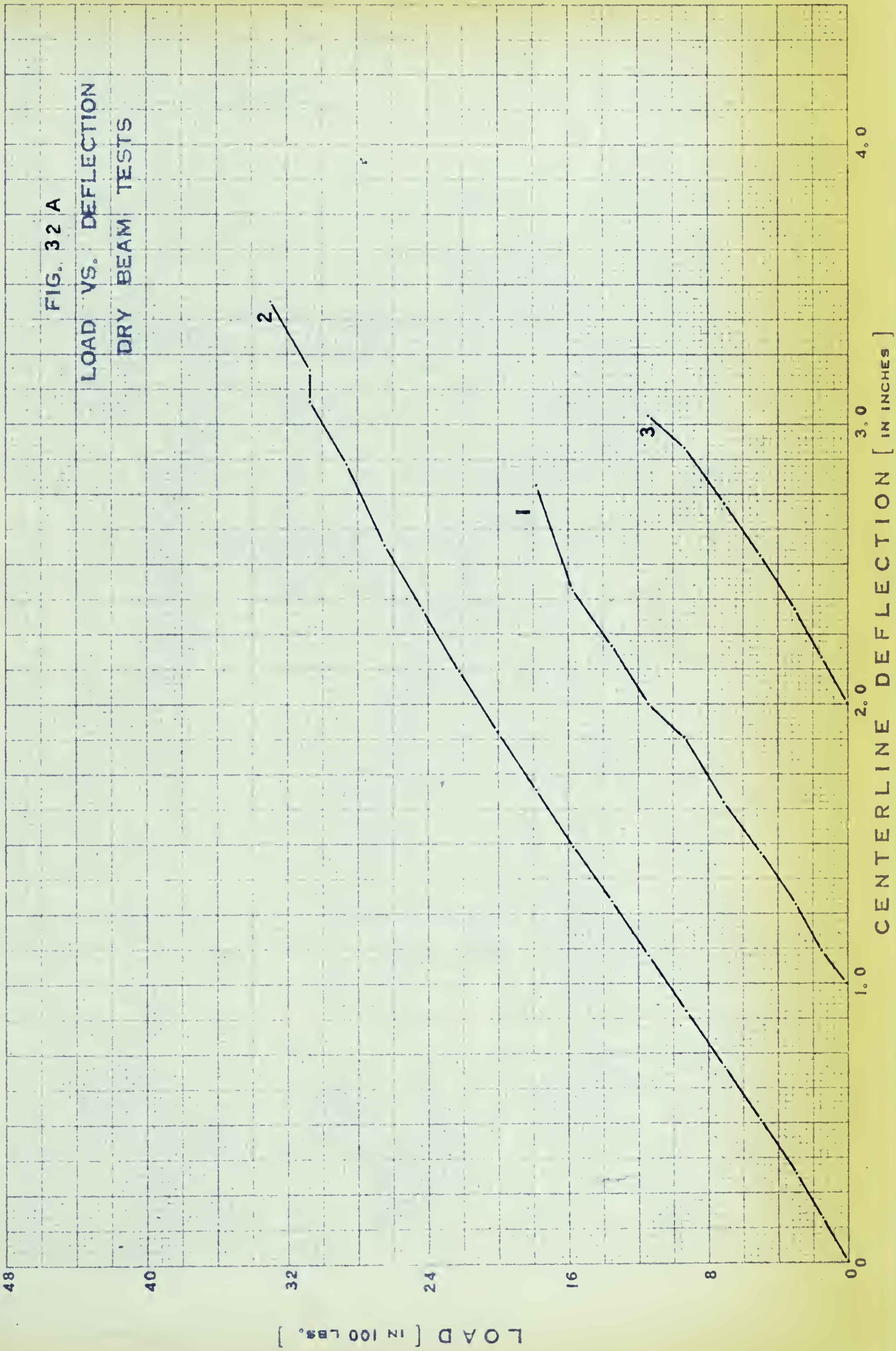


FIG. 32 A
LOAD VS. DEFLECTION
DRY BEAM TESTS
1
2
3
LOAD [IN 100 LBS.]
0
8
16
24
32
40
48
CENTERLINE DEFLECTION [IN INCHES]
0
1.0
2.0
3.0
4.0

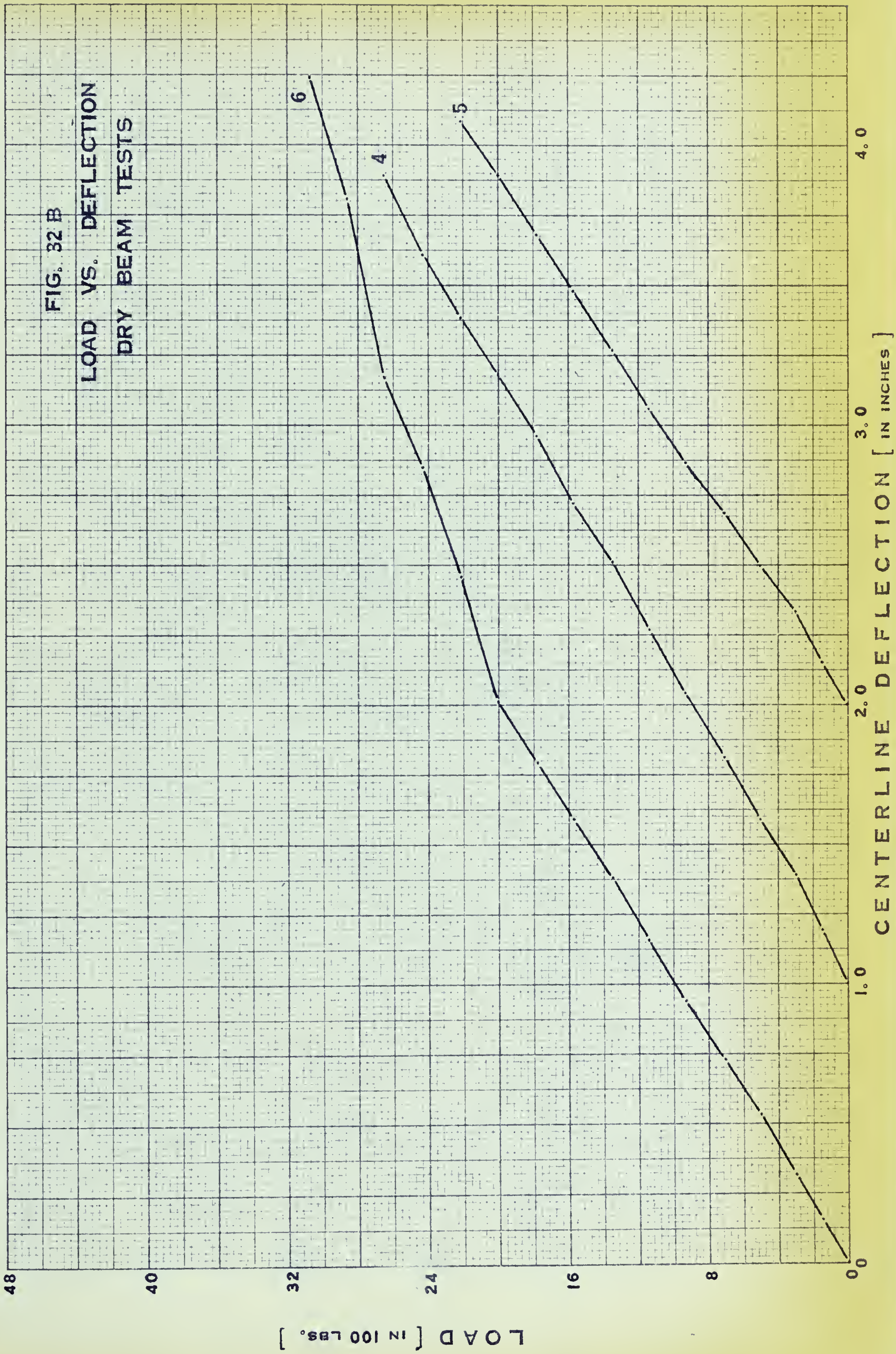


FIG. 32 B
LOAD VS. DEFLECTION
DRY BEAM TESTS
6
4
5
0
8
16
24
32
40
48
1.0
2.0
3.0
4.0
LOAD [IN 100 LBS.]
CENTERLINE DEFLECTION [IN INCHES]

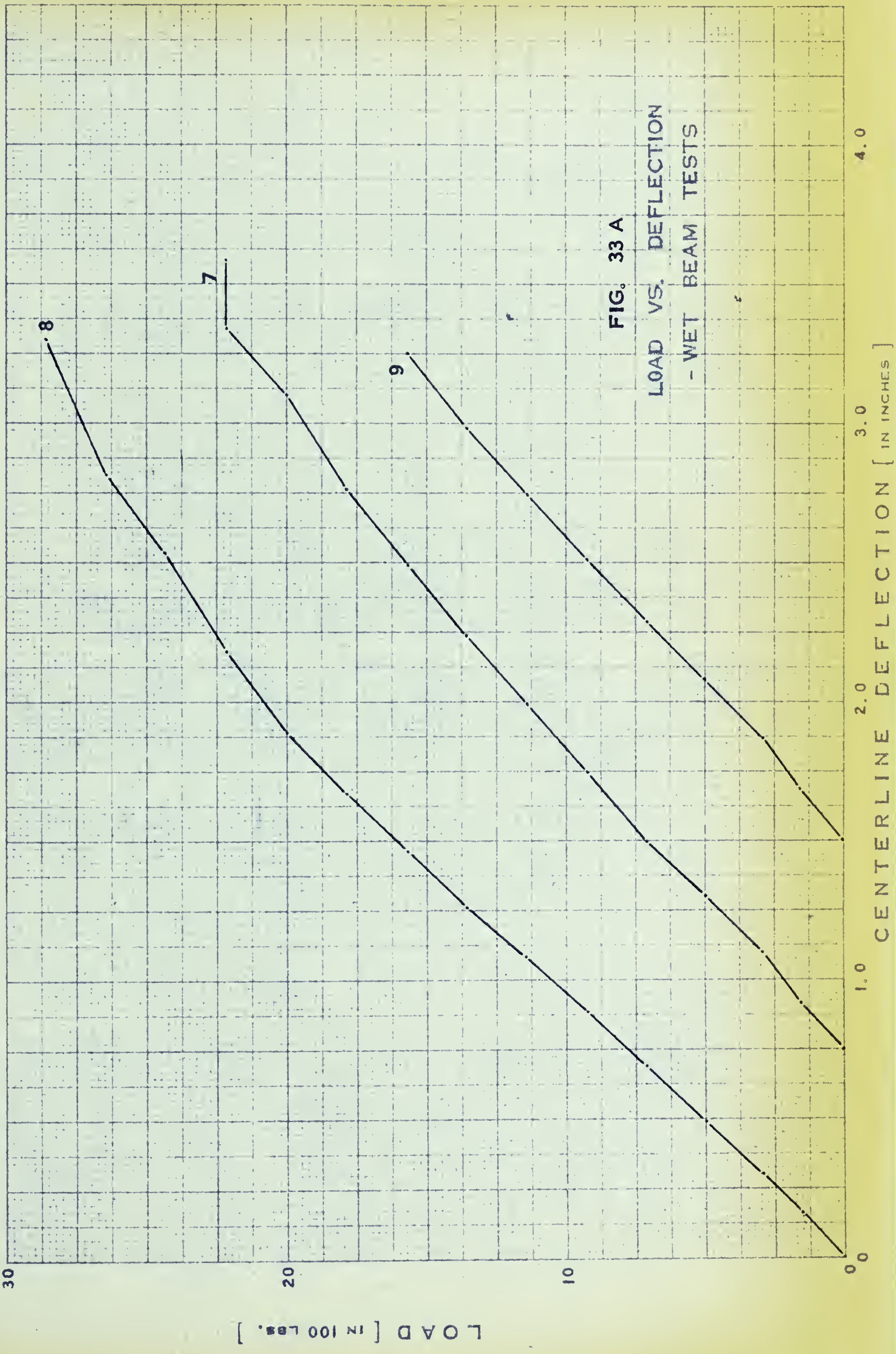


FIG. 33 A
LOAD VS. DEFLECTION
- WET BEAM TESTS
LOAD [IN 100 LBS.]
CENTERLINE DEFLECTION [IN INCHES]
0
10
20
30
0
1.0
2.0
3.0
4.0
7
8
9

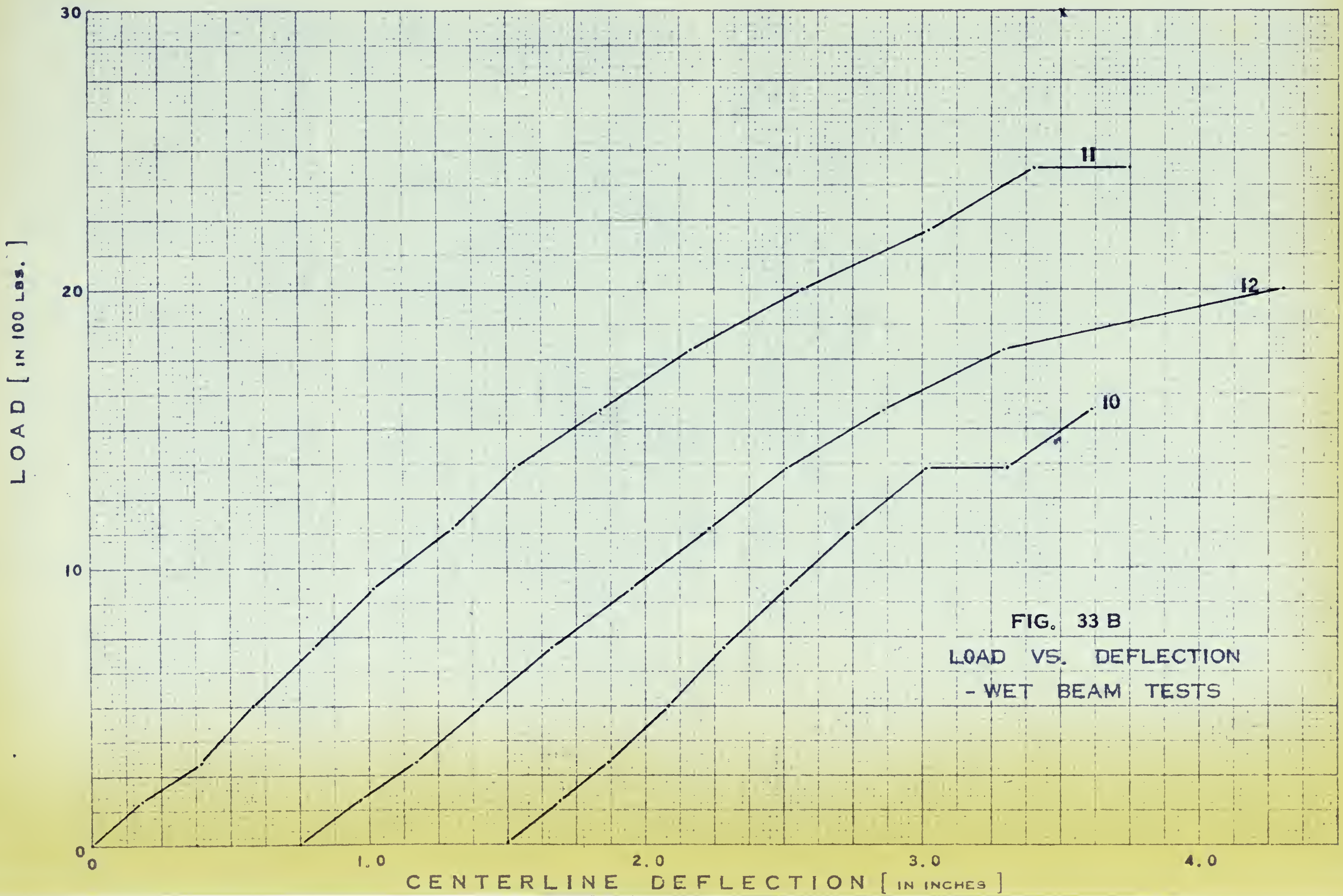


FIG. 33 B
LOAD VS. DEFLECTION
- WET BEAM TESTS

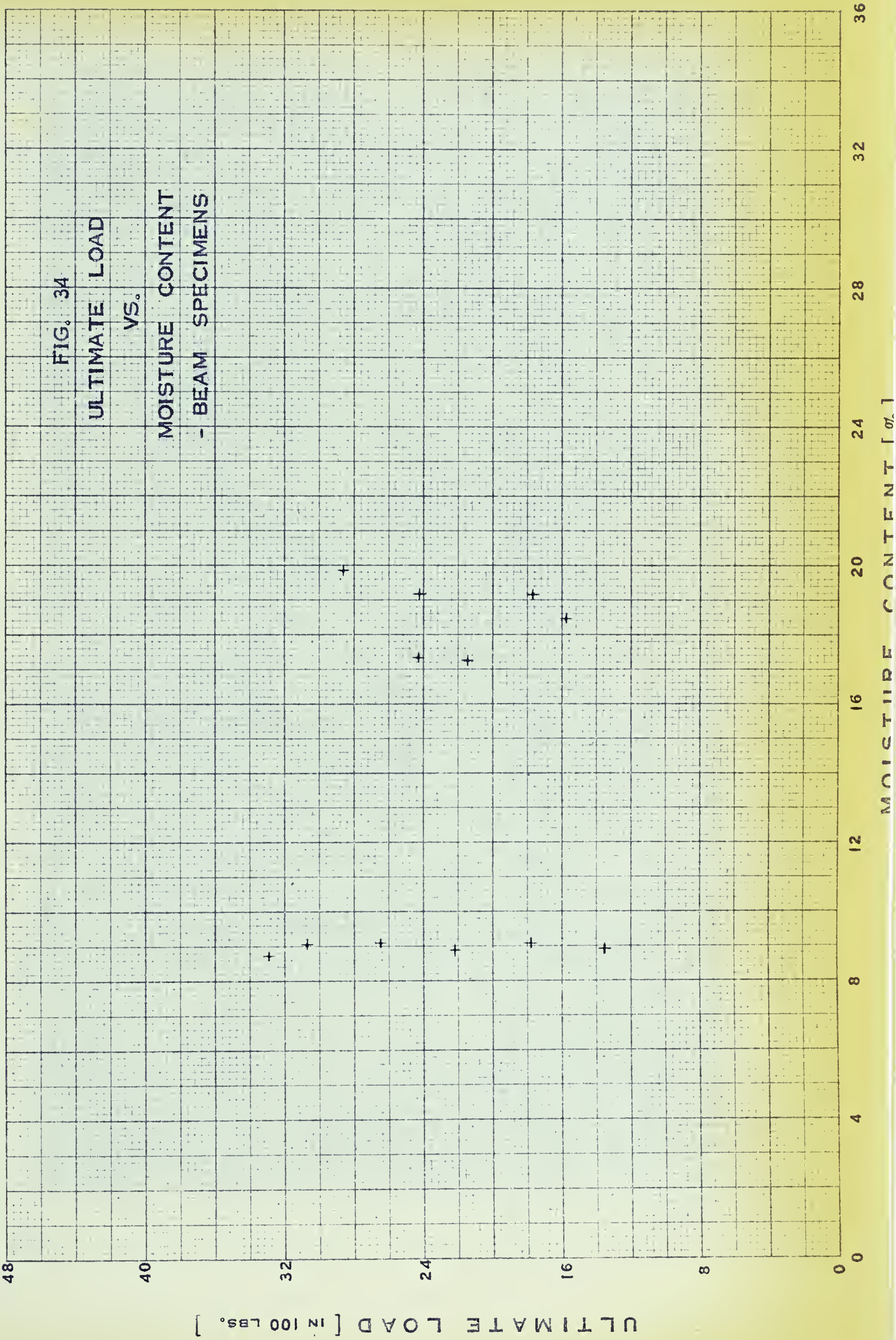


FIG. 34
ULTIMATE LOAD
VS.
MOISTURE CONTENT
- BEAM SPECIMENS
ULTIMATE LOAD [IN 100 LBS.]
MOISTURE CONTENT [%]
0
4
8
12
16
20
24
28
32
36
8
16
24
32
40
48

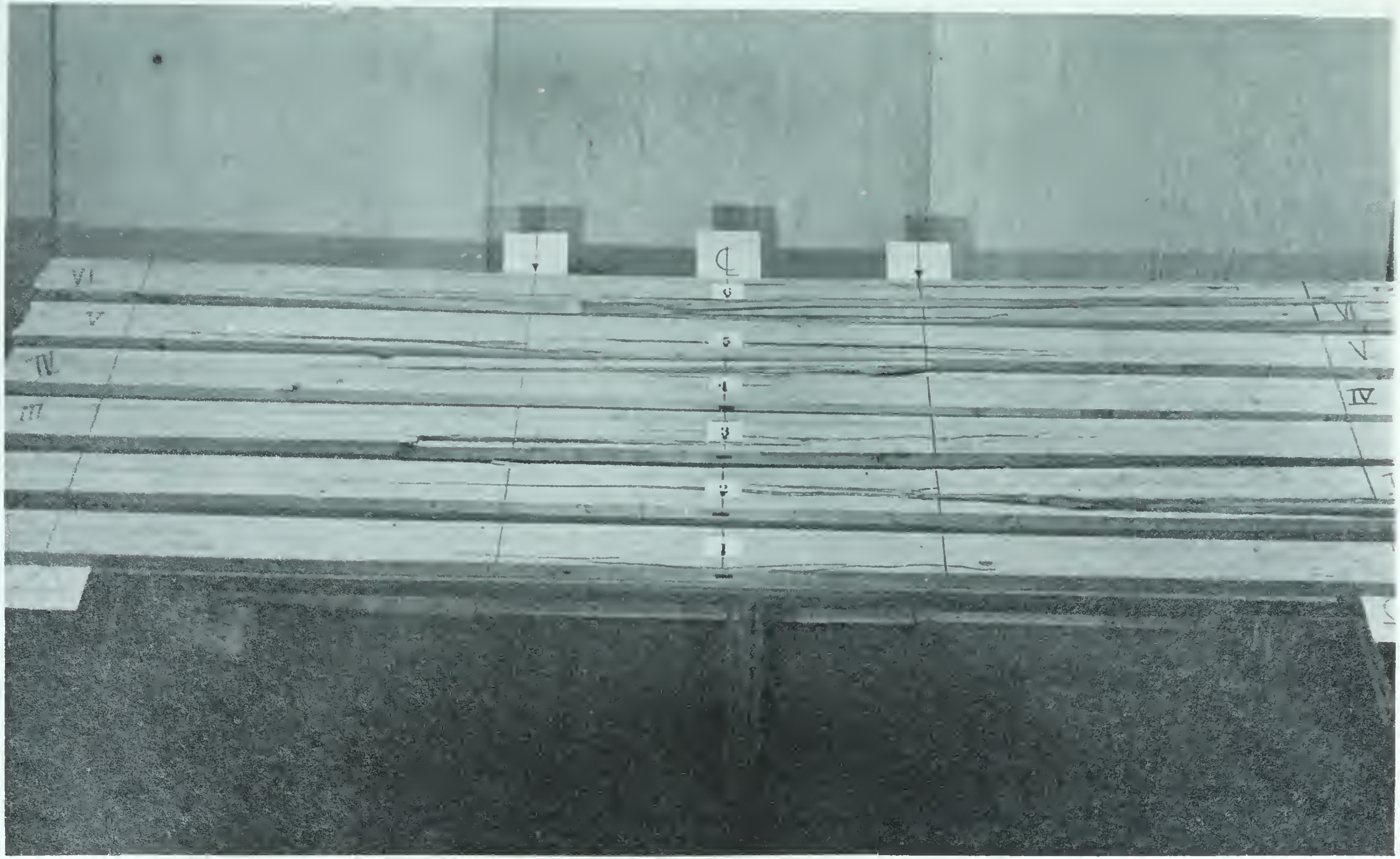


FIGURE 35. - View of Failures - Dry Beam Specimens.

FIGURE 36. - View of Failures - Wet Beam Specimens.

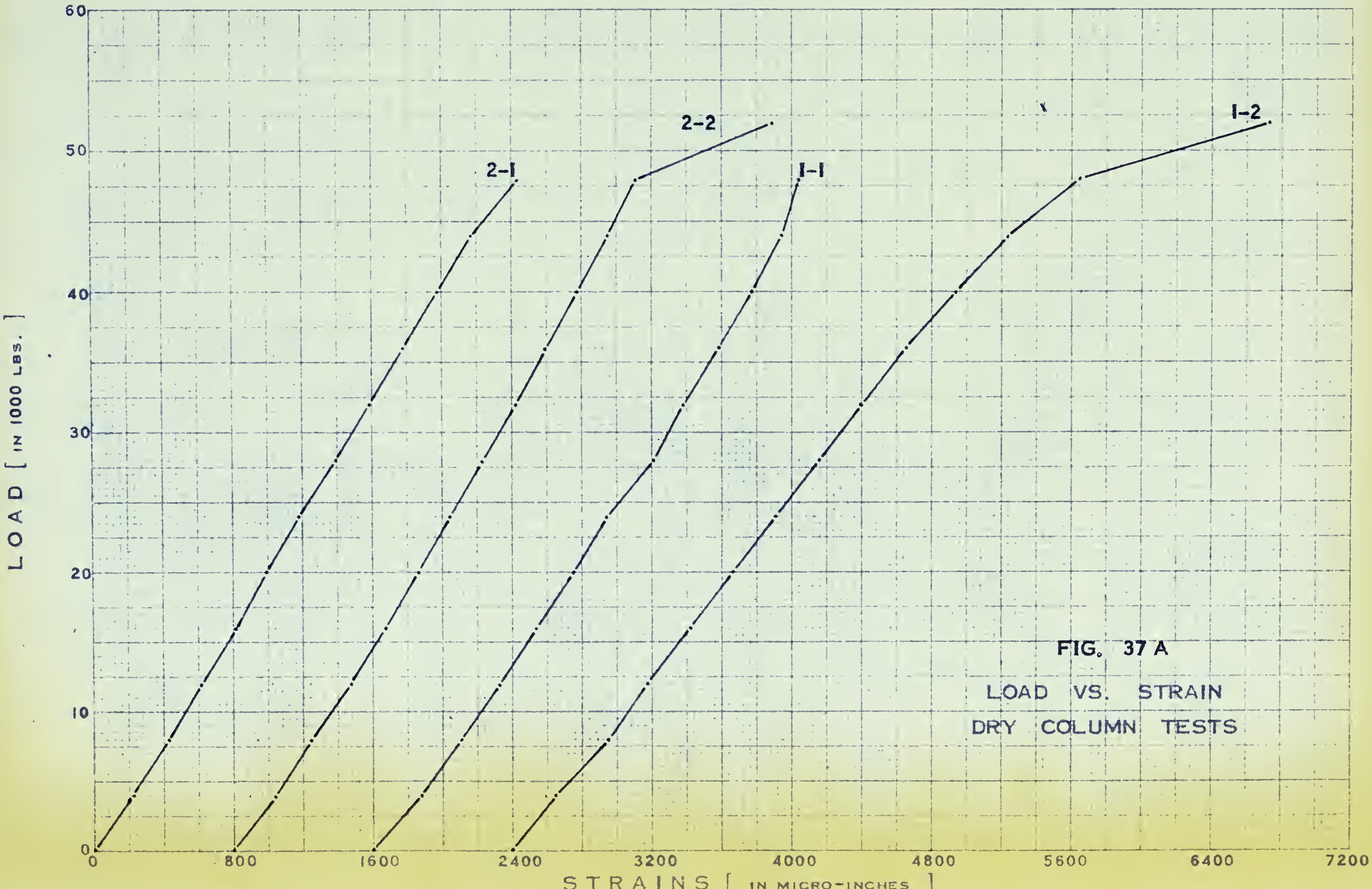


FIG. 37 A

LOAD VS. STRAIN

DRY COLUMN TESTS

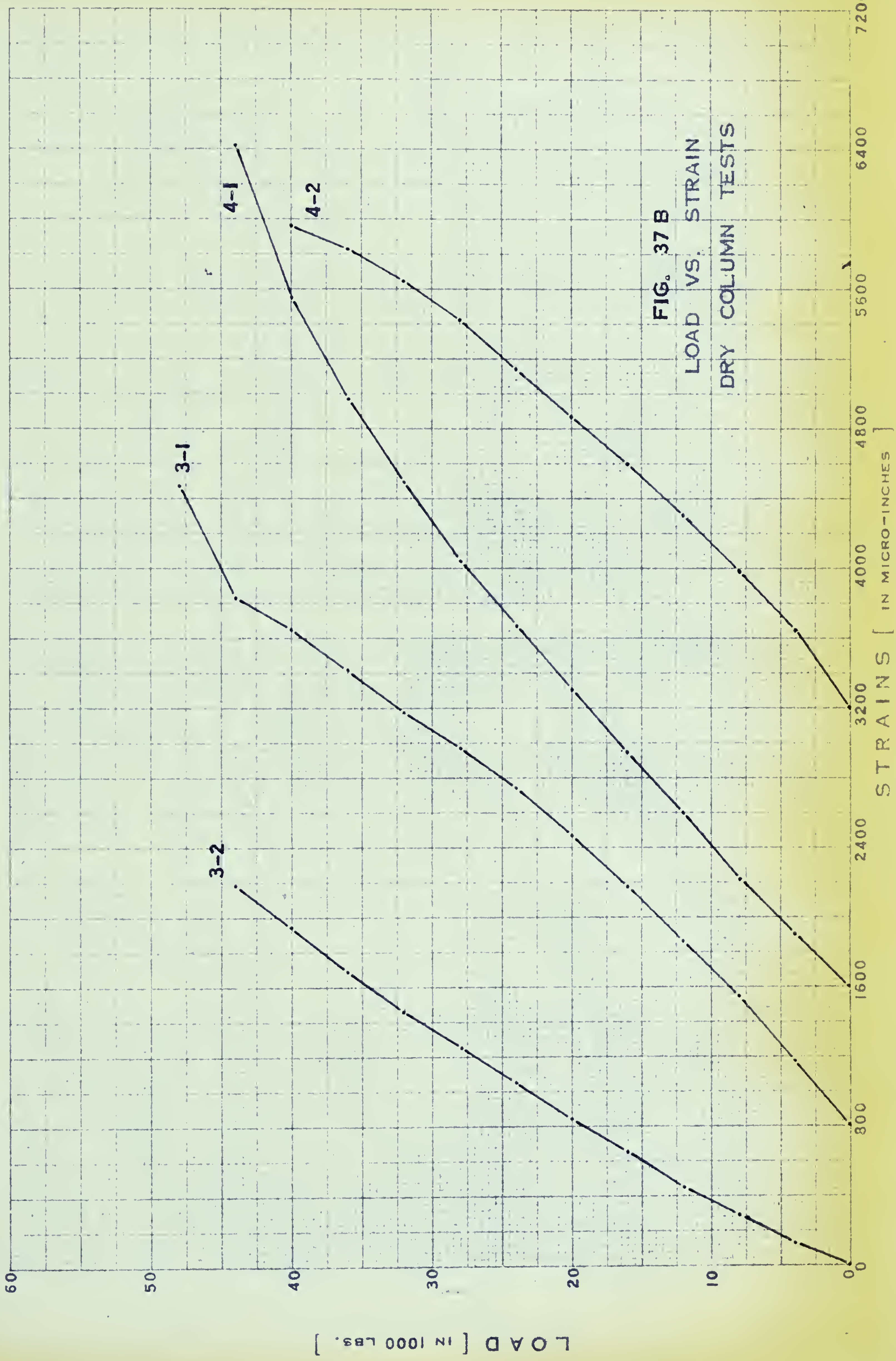


FIG. 37 B
LOAD VS. STRAIN
DRY COLUMN TESTS

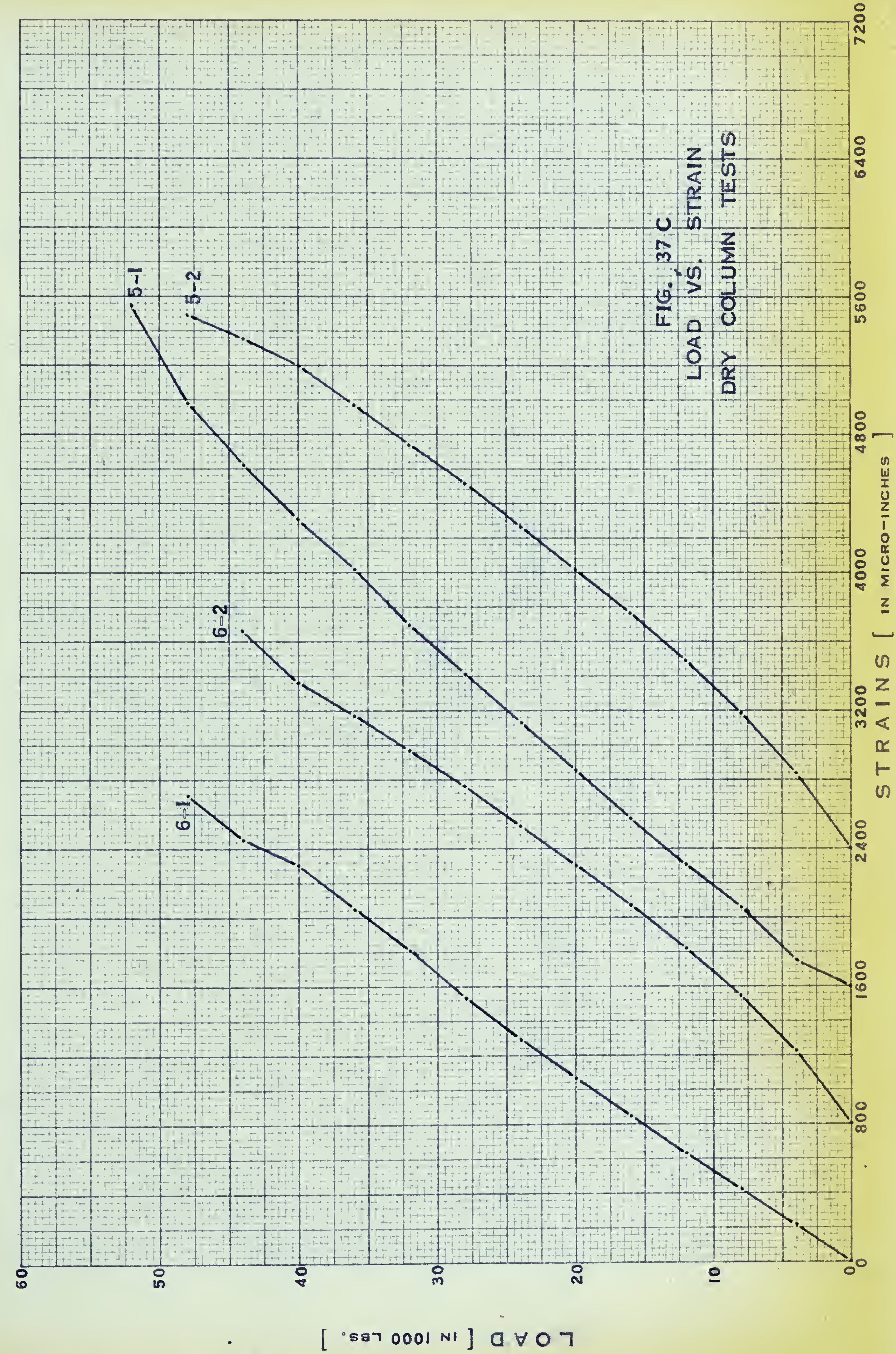


FIG. 37 C
LOAD VS. STRAIN
DRY COLUMN TESTS

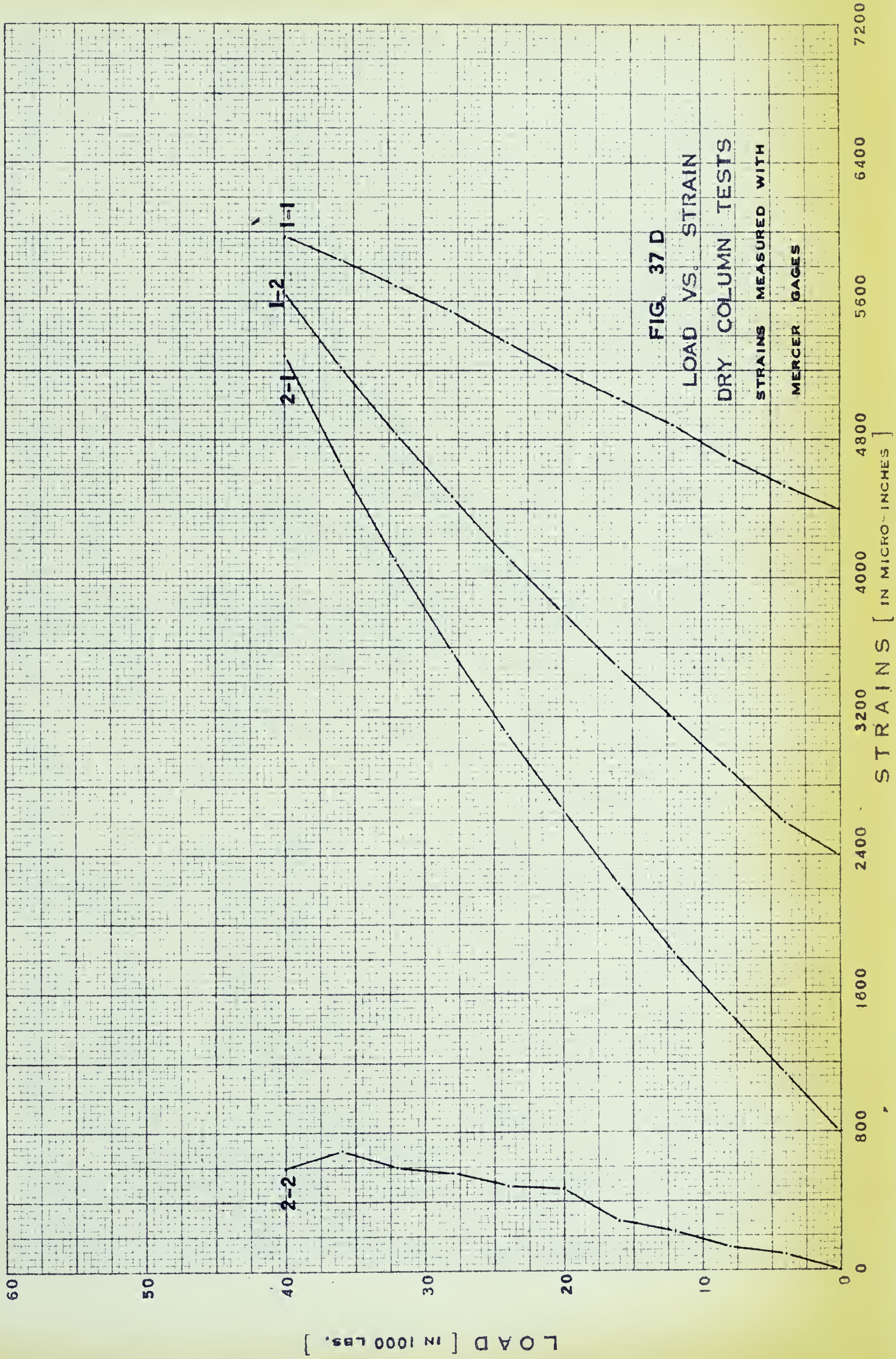


FIG. 37 D
LOAD VS. STRAIN
DRY COLUMN TESTS
STRAINS MEASURED WITH
MERCER GAGES
1-1
1-2
2-1
2-2
STRAINS [IN MICRO-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400
7200
LOAD [IN 1000 LBS.]
0
10
20
30
40
50
60

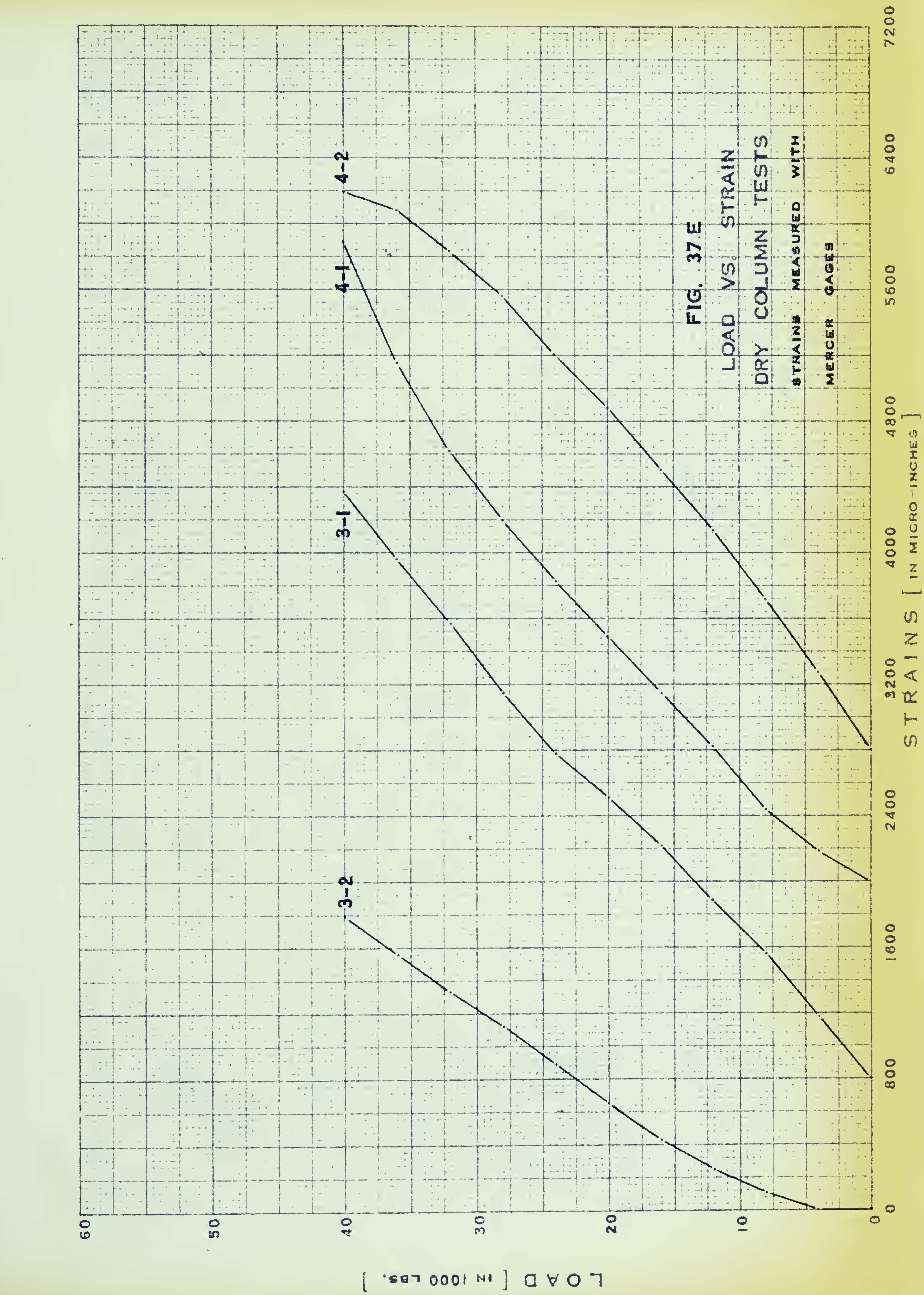


FIG. 37 E
LOAD VS. STRAIN
DRY COLUMN TESTS
STRAINS MEASURED WITH
MERCER GAGES
4-2
4-1
3-1
3-2
STRAINS [IN MICRO-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400
7200
LOAD [IN 1000 LBS.]
0
10
20
30
40
50
60

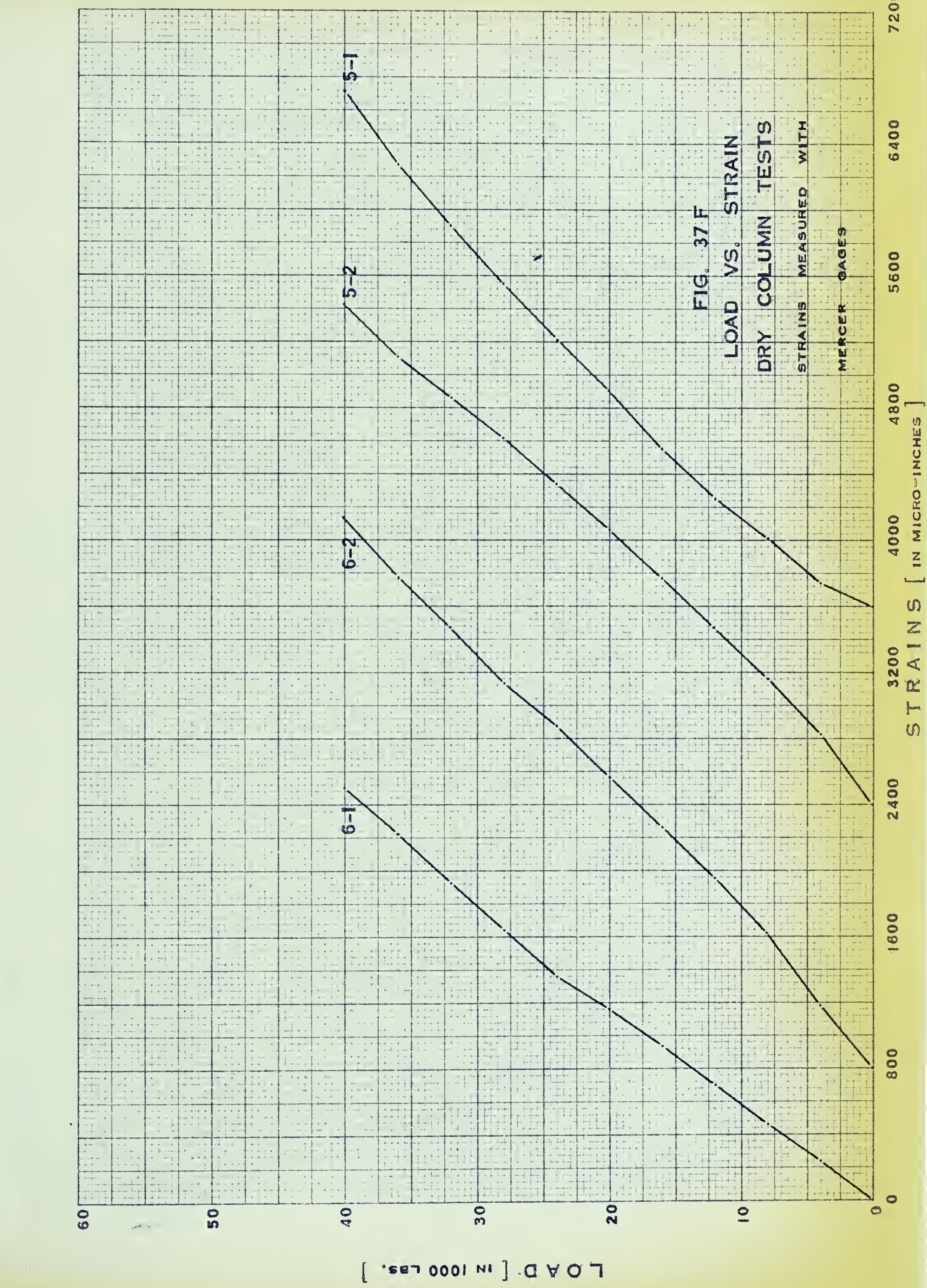


FIG. 37 F
LOAD VS. STRAIN
DRY COLUMN TESTS
STRAINS MEASURED WITH
MERCER GAGES
5-1
5-2
6-2
6-1
0
800
1600
2400
3200
4000
4800
5600
6400
7200
STRAINS [IN MICRO-INCHES]
0
10
20
30
40
50
60
LOAD [IN 1000 LBS.]

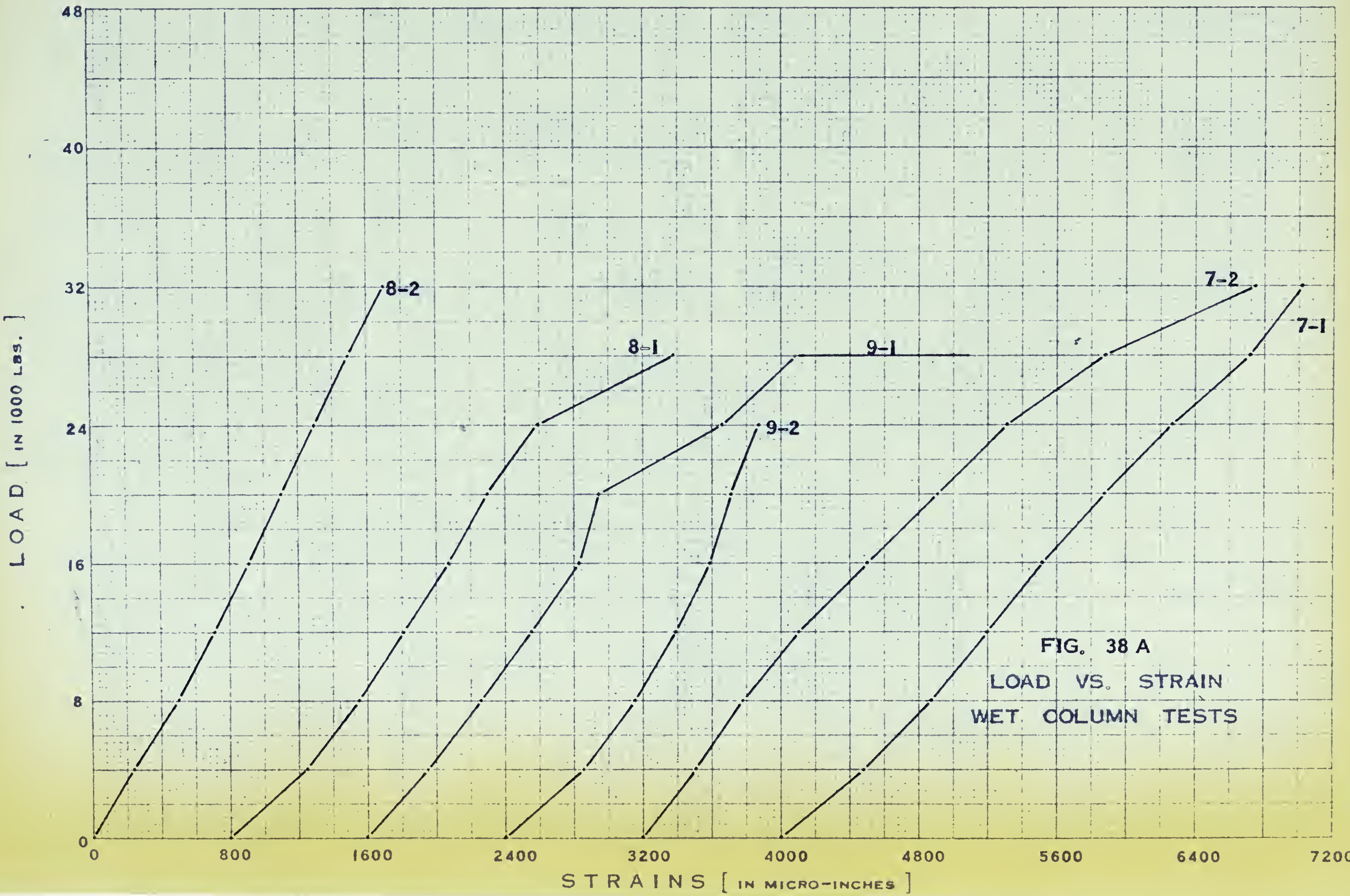


FIG. 38 A
LOAD VS. STRAIN
WET COLUMN TESTS

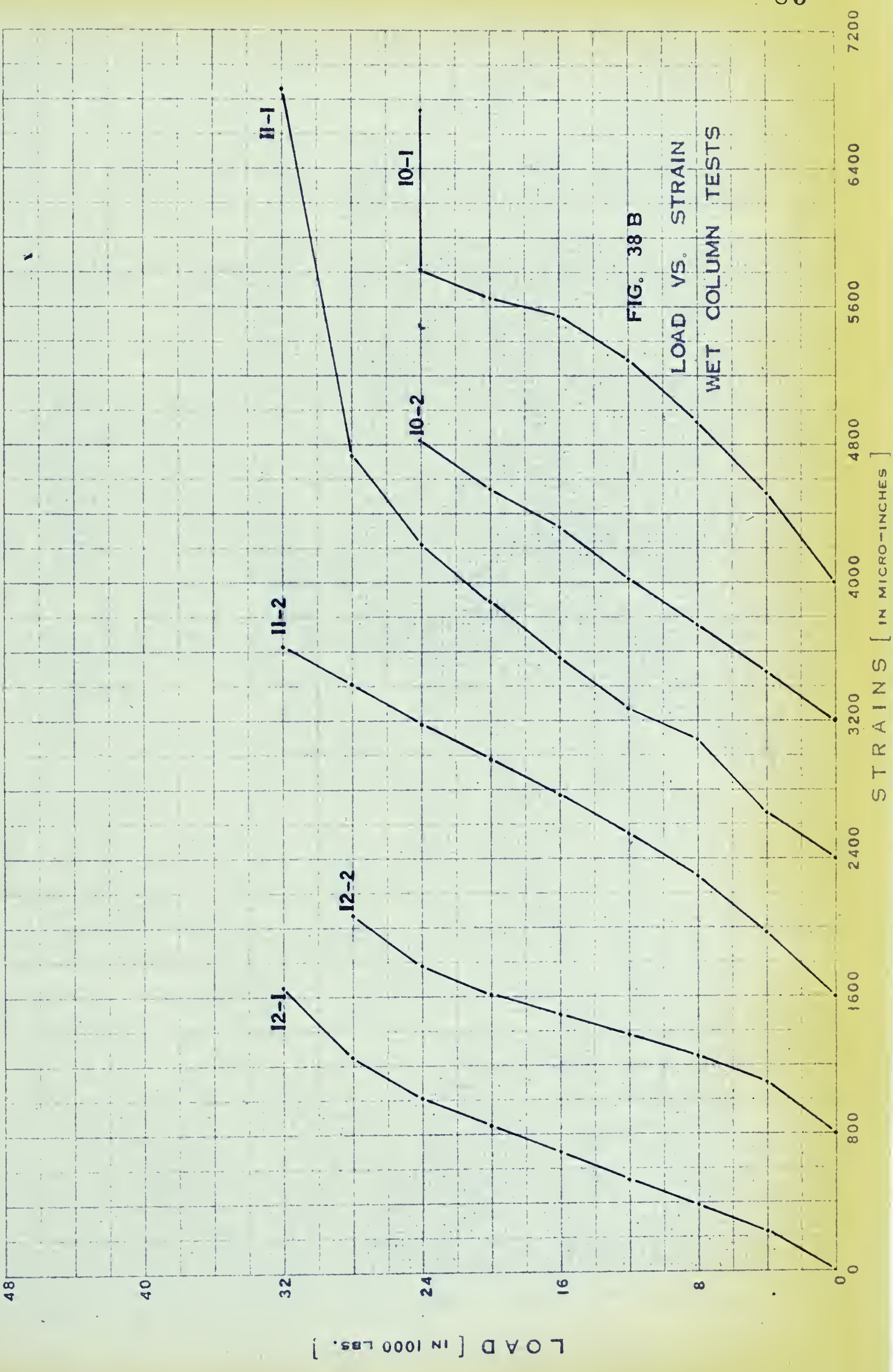


FIG. 38 B
LOAD VS. STRAIN
WET COLUMN TESTS

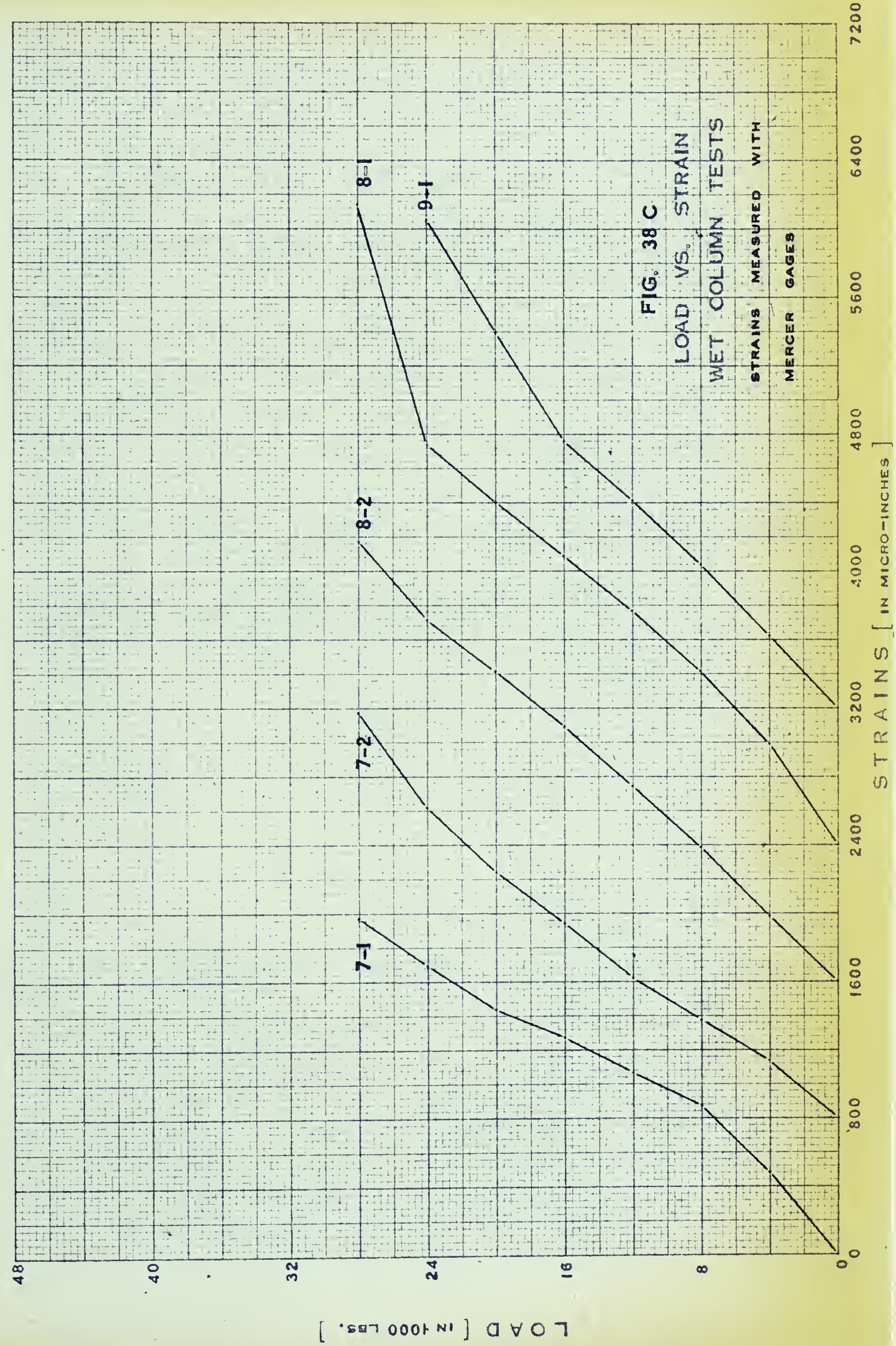


FIG. 38 C
LOAD VS. STRAIN
WET COLUMN TESTS

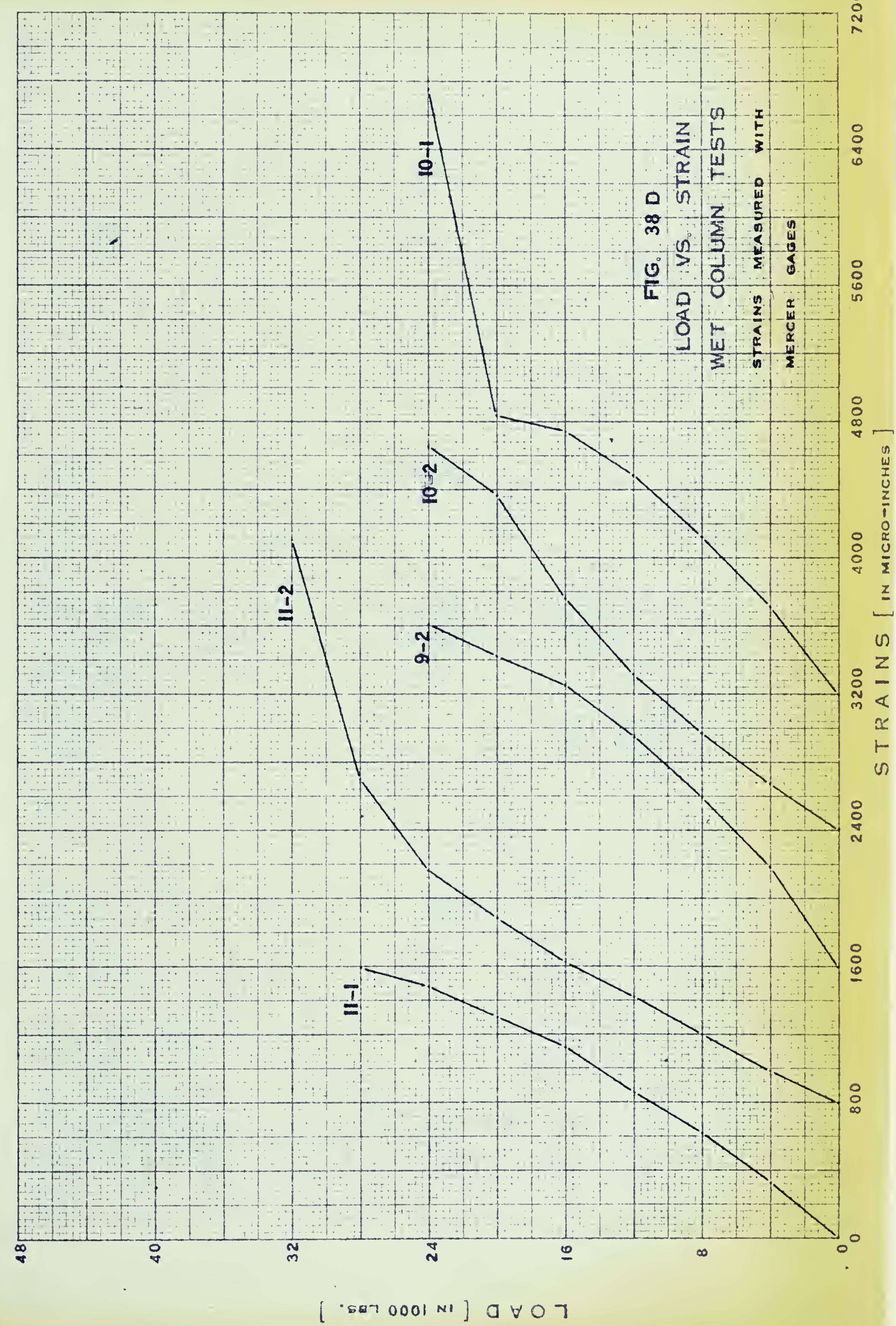


FIG. 38 D
LOAD VS. STRAIN
WET COLUMN TESTS
STRAINS MEASURED WITH
MERCER GAGES
10-1
10-2
9-2
11-2
11-1
LOAD [IN 1000 LBS.]
48
40
32
24
16
8
0
STRAINS [IN MICRO-INCHES]
0
800
1600
2400
3200
4000
4800
5600
6400
7200

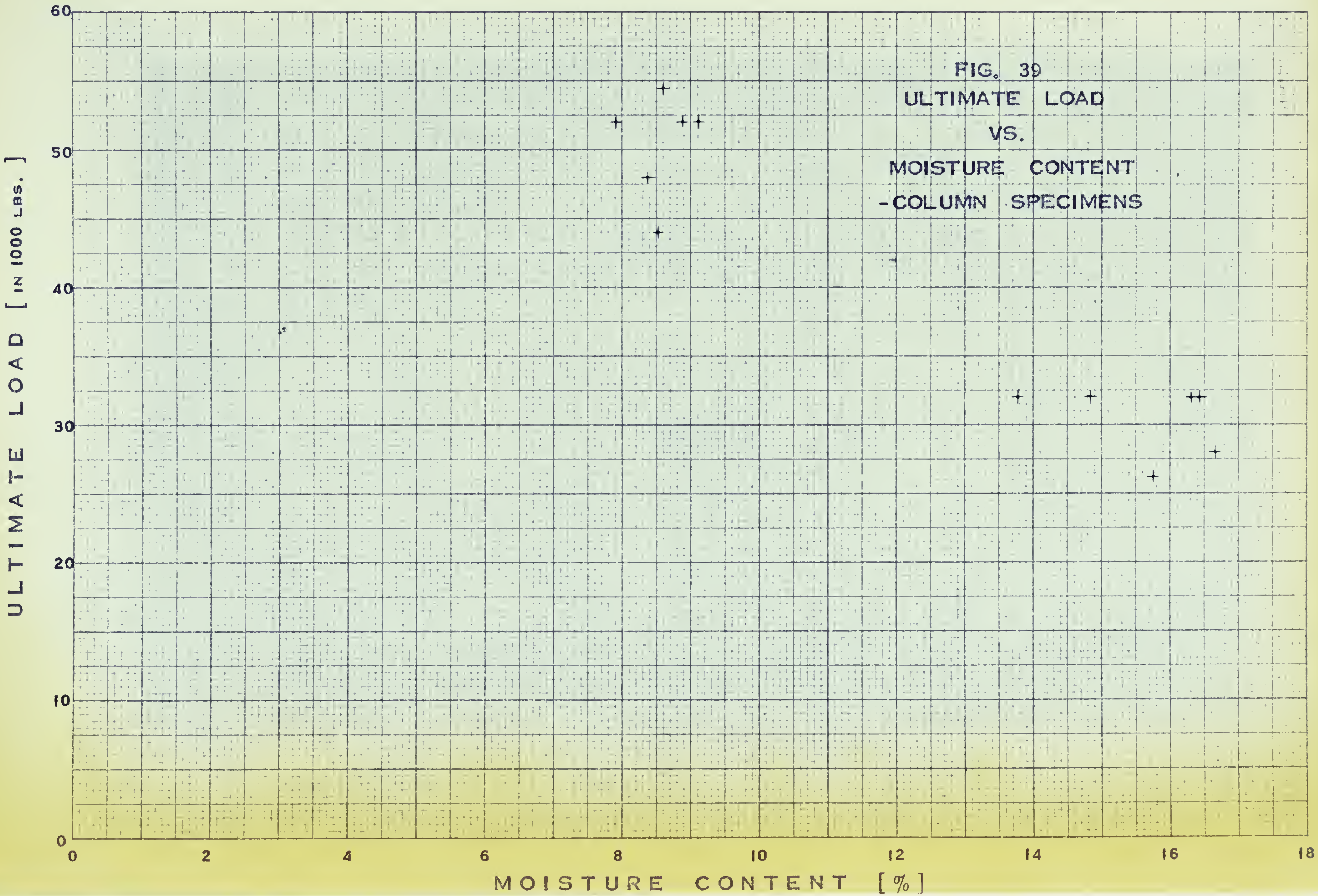


FIG. 39 ULTIMATE LOAD VS. MOISTURE CONTENT -COLUMN SPECIMENS

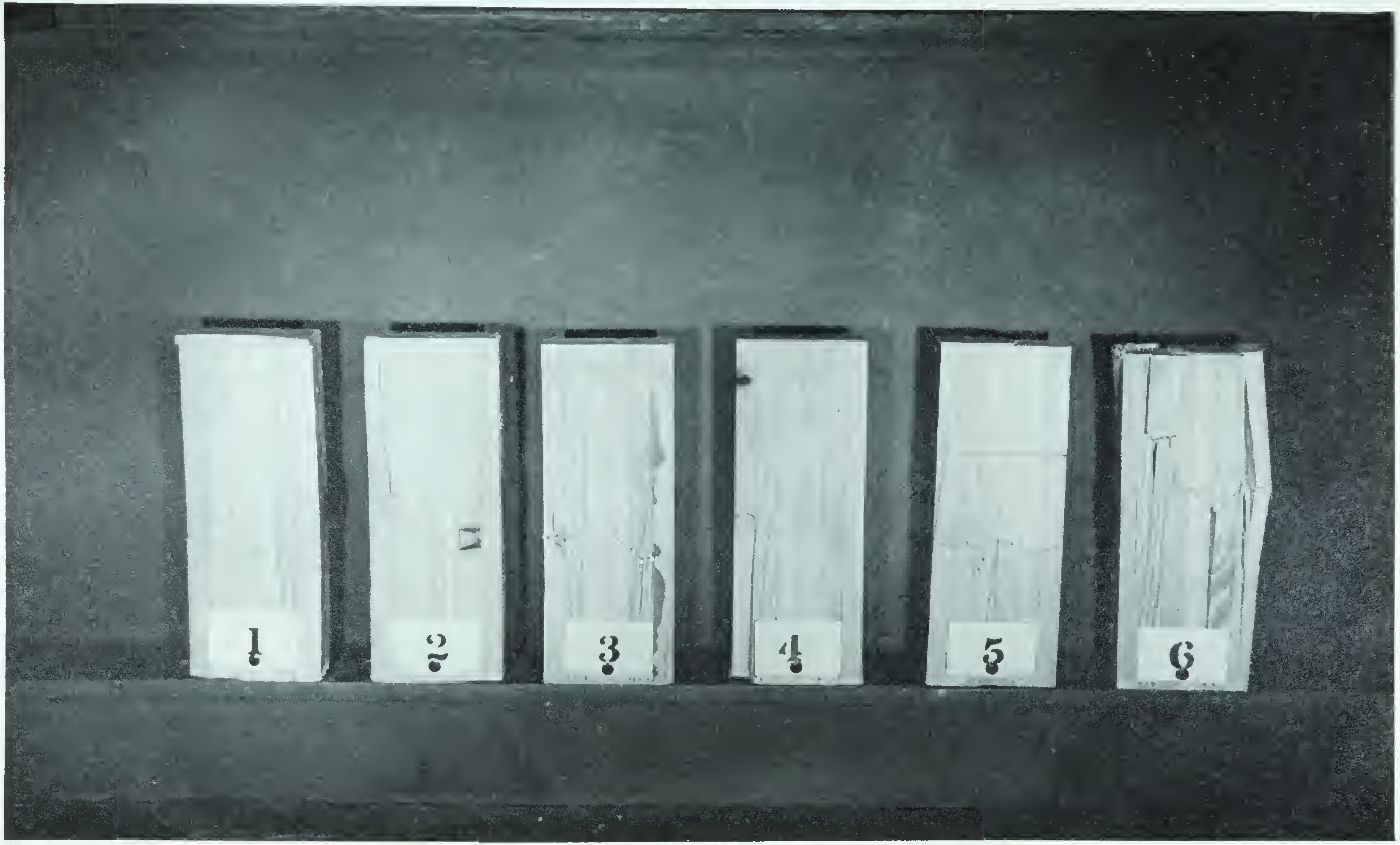


FIGURE 40. - View of Failures- Dry Column Specimens.

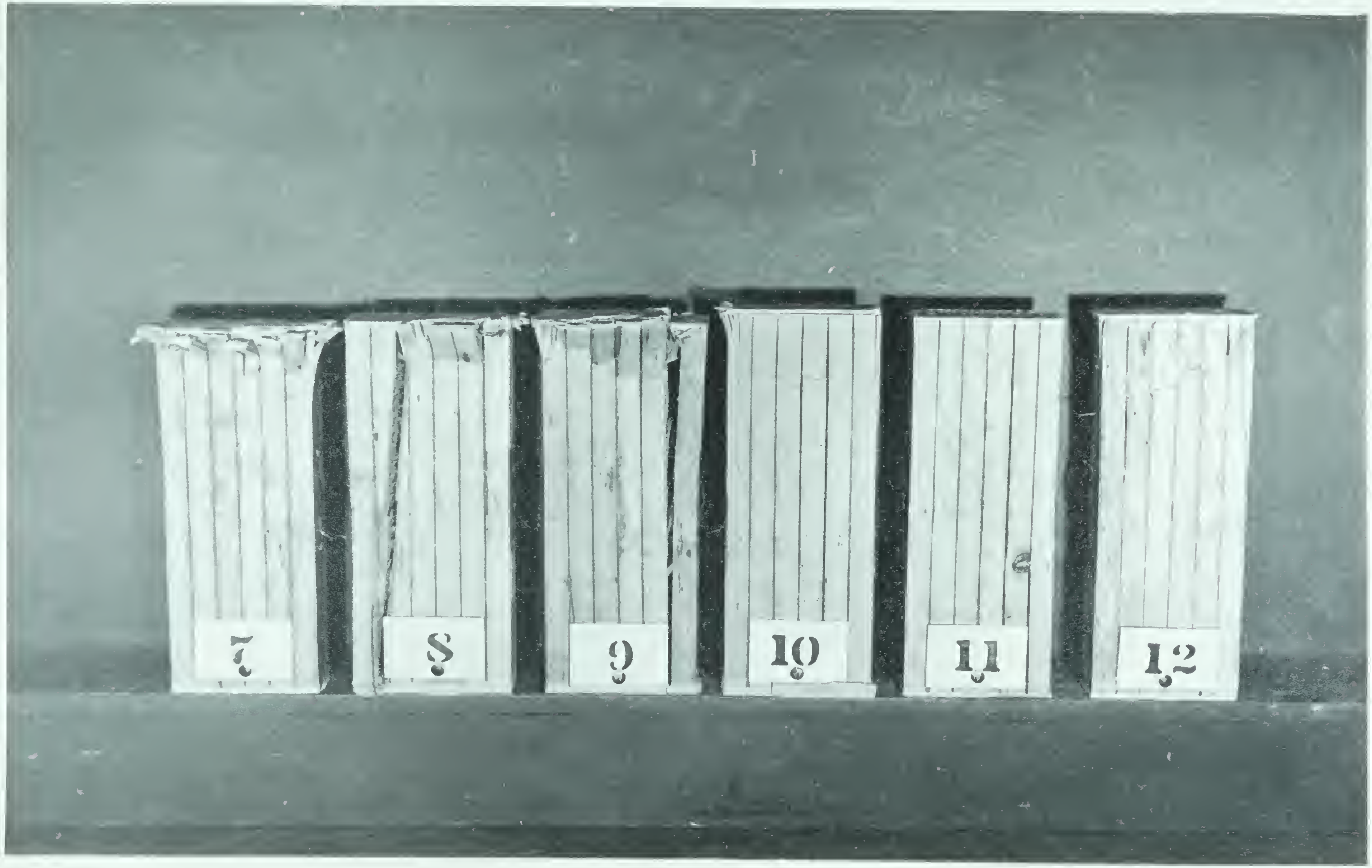


FIGURE 41. - View of Failures - Wet Column Specimens.

Data shown in Tables 1, 2 and 3 was computed as follows:

1. Arch Tests

In computations for the arch specimens it was assumed that bending stresses were linearly distributed across the depth of the beam and that original geometrical conditions of the arch existed.

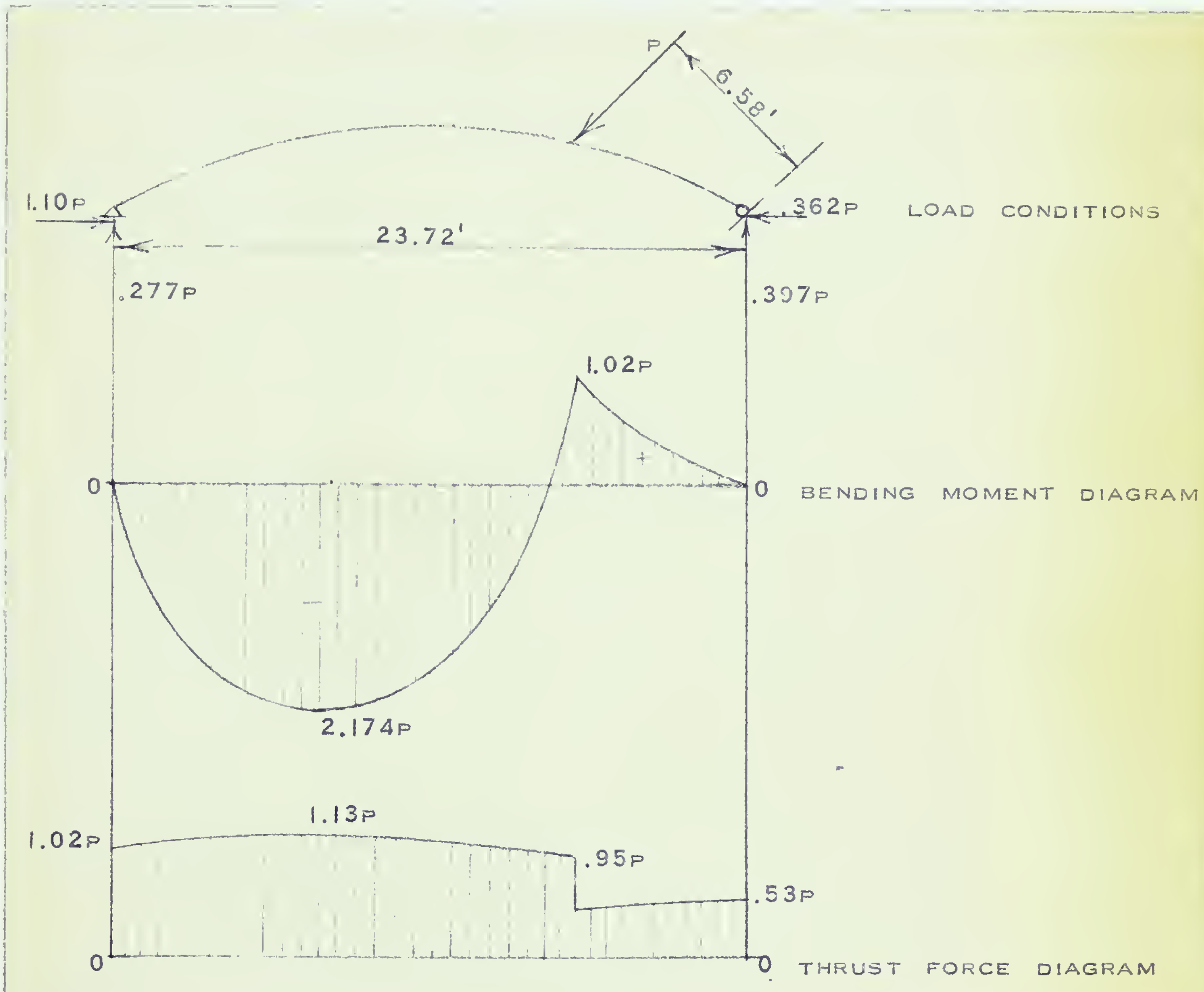


FIGURE 42 - THEORETICAL THRUST AND MOMENT DIAGRAMS - ARCH TESTS

a) Maximum shear stress in the vicinity of the load point was computed as follows:

$$\text{Maximum shear stress (Lbs./in.}^2) = \frac{3\ (V \cos\alpha + H \sin\alpha)}{2\ A}$$

$$= \frac{3\ (0.277\ P \cos 20^\circ 02' + 1.10 \sin 20^\circ 02')}{2\ A} = \frac{.956\ P}{A}$$

where P = ultimate load in Lbs.

V = 0.277 P = vertical hinge reaction in Lbs.

H = 1.10 P = horizontal hinge reaction in Lbs.

A = cross sectional area of arch in in.^{2}.

α = $20^\circ 02'$ = angle between radial and vertical line in vicinity of load point.

b) Thrust in the vicinity of the maximum moment was determined by:

$$\text{Thrust (Lbs./in.}^2) = \frac{H \cos\alpha' + \sin\alpha'}{A}$$

$$= \frac{1.10\ P \cos 13^\circ 25' + 0.277\ P \sin 13^\circ 25'}{A}$$

where α' = $13^\circ 25'$ = angle between radial and vertical line in vicinity of maximum moment.

c) Maximum tensile and compressive stresses were computed as follows:

$$f = \frac{P'}{A} \pm \frac{Mc}{I}$$

where f = modulus of rupture in Lbs./in.^{2}.

P' = thrust in Lbs. at section under consideration.

A = cross sectional area of arch in in.^{2}.

M = moment in inch Lbs.

c = distance from neutral axis to the outermost fiber in inches.

I = moment of inertia of the cross section about the neutral axis.

d) Modulus of elasticity in tension and compression was determined from the slope of the load strain graph.

2. <u>Beam Tests</u>

a) Modulus of Rupture.

Modulus of rupture was determined using the formula $f = \frac{Mc}{I}$.

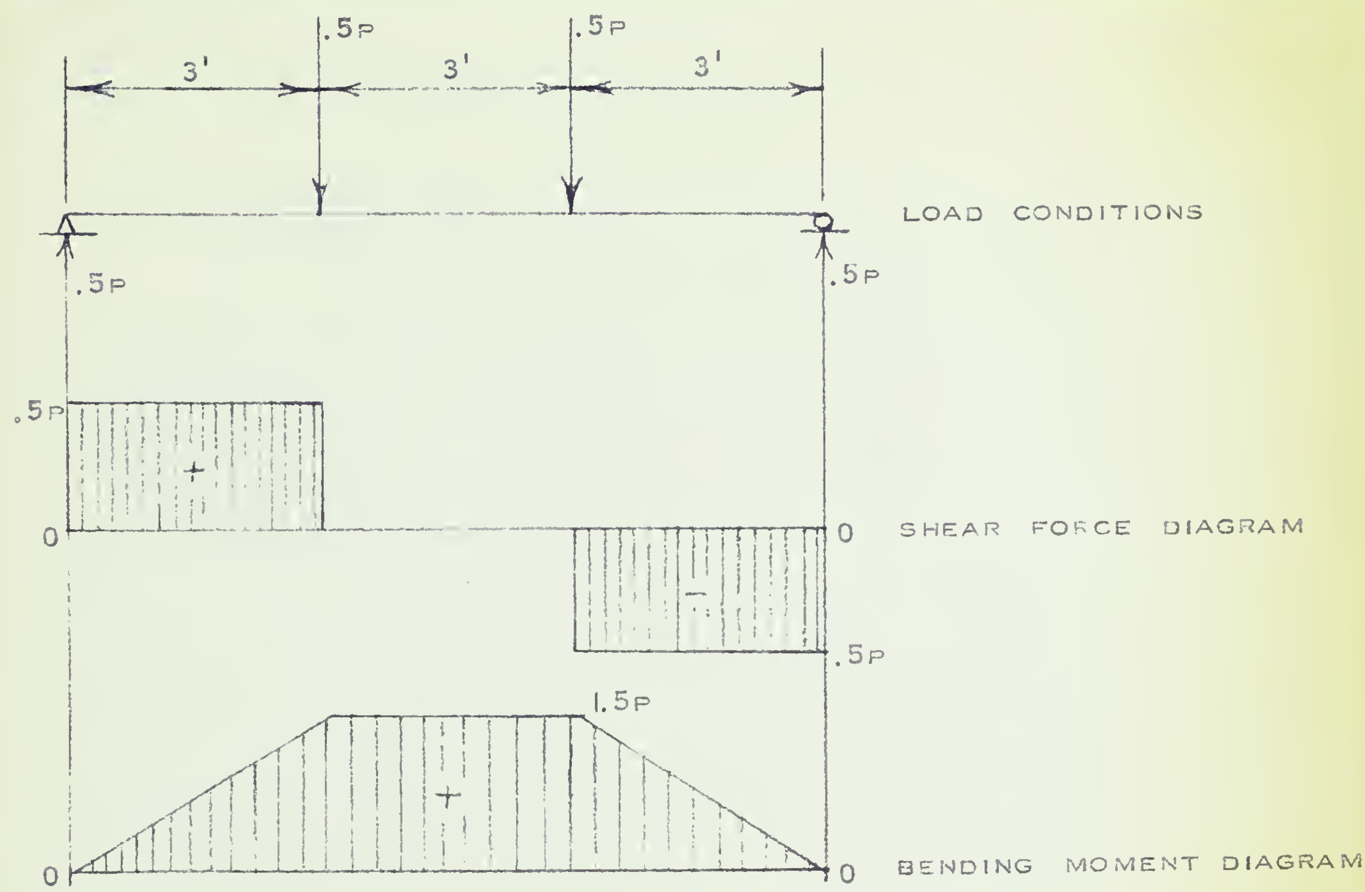


FIGURE 43 - THEORETICAL SHEAR AND MOMENT DIAGRAMS - BEAM TESTS

From the above sketch the maximum moment M = 1.5 P Ft. Lbs. where P is the total load in Lbs. The term c = half depth (in inches) of the beam = $\frac{h}{2}$ and I, the moment of inertia is equal to $\frac{1}{12}$ b h ^{3}. Making these substitutions in the above formula and reducing, the following expression is obtained

$$f = \frac{108\ P}{A\ h}$$

where A = cross sectional area in in^2.

h = total depth of the beam in inches.

P = total load in Lbs.

f = modulus of rupture in Lbs./in.^{2}.

b) Modulus of elasticity in bending was computed by two methods - one based on deflection at centerline; the other based on strains recorded by strain gauges.

i) Deflection Method

Centerline deflection in a beam subjected to third point loading can be expressed as follows:

$$\Delta = \frac{\frac{1}{2} P a (3 L^2 - 4 a^2)}{24 E I} \text{ from which } E = \frac{\frac{1}{2} P a (3 L^2 - 4 a^2)}{24 I \Delta}$$

Reducing this according to the conditions in these tests, the following expression is obtained:

$$E = \frac{22356}{I} \left(\frac{P}{\Delta}\right)$$

where E = modulus of elasticity in Lbs./in.^{2}.

P = total applied load in Lbs.

I = moment of inertia (in in.^{4}) of the beam cross section about the neutral axis.

Δ = centerline deflection in inches at the load P

ii) Strain Method

The modulus of elasticity was computed from the slope of the load-strain graph.

c) Maximum shear stress at failure was computed using the formula $H = \frac{VQ}{Ib}$ which reduces to the form $H = 3/4 \frac{P}{A}$.

where H = horizontal shear stress (Lbs./in.^{2}).

P = total load in Lbs.

A = cross sectional area of beam in in.^{2} .

3. Column Tests

a) Ultimate compression stress parallel to the grain was determined by dividing the ultimate load by the cross-sectional area of the column.

b) Modulus of elasticity in compression was computed from the slope of the load strain graph.

4. Moisture Contents and Specific Gravity

a) Moisture contents were calculated using the formula

$$W = \frac{(W_w - W_d)}{W_d} \times 100\%$$

where W = moisture content in %.

W_w = wet weight of sample in grams.

W_d = dry weight of sample in grams.

b) Specific gravities were determined using the expression

$$\text{Specific Gravity} = \frac{W_d}{(W_d + W_s) - V_p}$$

where W_d = dry weight of sample in grams.

W_s = loss of weight in water (in grams).

V_p = volume of paraffin in cc.

The term $(W_d + W_s)$ = volume of paraffin coated sample in cc.

TABLE 1

ARCH DATA

Arch No.	Cross Sectional Area	Ultimate Load	Maximum Deflection at *Position 2	Maximum Thrust at Position 2	Max. Shear Stress	Max. Tensile Stress at Position 2	Max. Compressive Stress at Position 2	Modulus of Elasticity (Tension)	Modulus of Elasticity (Compression)	Moisture Content	Specific Gravity	Type of Failure
	In.^{2}	Lbs.	In.	Lb/In.^{2}	Lb/In.^{2}	Lb./In.^{2}	Lb./In.^{2}	Lb/In.^{2} x10^6	Lb/In.^{2}x10^6	%		
						DRY ARCH TESTS						
1	6.84	1,415	6.90	235	198	6,961	7,431	2.35	1.92	10.83	0.57	C.G.T.F.
2	6.74	1,372	7.50	231	195	6,866	7,328	2.22	2.24	8.49	0.58	STF & GF
3	6.76	1,200	6.18	201	170	6,000	6,402	2.05	1.91	7.91	0.54	S.H.T.F.
4	6.77	1,307	8.40	219	185	6,482	6,920	1.52	1.82	9.53	0.58	C.G.T.F.
5	6.75	1,415	9.90	238	200	7,053	7,529	1.57	1.72	10.32	0.64	S.P.T.F.
6	6.80	1,049	5.80	175	147	5,196	5,546	1.77	1.72	9.59	0.55	C.G.C.F.
** Ave.	6.77	1,341	7.77	224	189	6,672	7,122	1.94	1.92	9.42	0.58	
						WET ARCH TESTS						
7	6.80	555	2.55	93	78	2,746	2,932	2.78	4.71	28.68	0.56	G.F.
8	6.87	662	5.43	109	92	3,228	3,446	4.33	3.14	27.53	0.53	G.F.
9	6.90	705	11.95	116	98	3,406	3,638	2.28	2.07	27.23	0.55	G.F.
10	6.92	641	4.55	105	89	3,102	3,313	1.93	1.89	30.21	0.55	SHTF & GF
11	6.92	555	4.50	91	77	2,686	2,868	2.75	1.89	28.43	0.54	G.F.
12	6.92	471	-	77	65	2,280	2,434	2.90	1.90	29.51	0.53	G.F.
Ave.	6.89	598	5.80	99	83	2,908	3,105	2.82	2.60	28.60	0.54	

C.G.T.F. - Cross-grain tension failure.
S.T.F. - Simple tension failure.
G.F. - Glue failure.
S.H.T.F. - Shattering tension failure.
S.P.T.F. - Splintering tension failure.
C.G.C.F. - Cross-grain compression failure.
** Average Values Exclude Values for Specimen 6.
* Position 2 - Location of maximum moment.

BEAM DATA

TABLE 2

Beam No.	Cross Sectional Area	Ultimate Load	Ultimate Deflection	Modulus of Rupture	Modulus of Elasticity Deflection	Modulus of Elasticity Strain Gauges	Maximum Shear Stress	Moisture Content	Specific Gravity	Type of Failure
	$Ins.^2$	Lbs.	In.	$Lbs/In.^2$	$Lbs/In^2 \times 10^6$	$Lbs/In.^2 \times 10^6$	Lbs/In^2	%		
				DRY BEAM TESTS						
1	6.65	1,785	1.78	6,544	2.29	2.53	201	9.08	0.56	S.H.T.F.
2	6.66	3,290	3.44	12,016	2.13	2.13	370	8.77	0.47	S.F.
3	6.56	1,355		5,035	2.10	2.26	155	8.93	0.53	S.T.F.
4	6.59	2,645	2.89	9,860	1.95	2.04	302	9.08	0.55	C.G.C.F.
5	6.60	2,215	2.08	8,181	2.21	2.51	252	8.92	0.51	S.T.F.
6	6.60	3,075	4.24	11,357	2.06	2.16	349	9.02	0.54	S.P.T.F.
* Ave.	6.61	2,806	3.16	10,353	2.08	2.21	318	8.95	0.52	
				WET BEAM TESTS						
7	6.87	2,430		9,452	1.70	4.31	265	19.20	0.53	C.G.T.F.
8	6.92	2,860	3.30	9,809	2.00	4.24	310	19.87	0.57	C.G.T.F.
9	6.86	1,785		6,231	1.76	8.92	195	19.17	0.54	C.G.T.F.
10	6.86	1,570	2.11	5,445	1.70	3.75	171	18.47	0.53	G.F.
11	6.86	2,430	3.75	8,427	1.66	3.27	266	17.37	0.53	S.H.T.F.
12	6.92	2,150		7,374	1.44	3.64	233	17.22	0.53	S.T.F.
Ave.	6.88	2,204	3.05	7,790	1.71	4.69	240	18.55	0.54	

S.H.T.F. - Shattering tension failure.
S.F. - Shear failure.
S.T.F. - Simple tension failure.
C.G.C.F. - Cross-grain compression failure.
S.P.T.F. - Splintering tension failure.
C.G.T.F. - Cross-grain tension failure.
G.F. - Glue failure.
* Average values exclude values for specimens 1 & 3

TABLE 3

COLUMN DATA

Column No.	Cross Sectional Area	Ultimate Load	Ultimate Compression Stress Parallel to Grain	Modulus of Elasticity SR-Gauges	Modulus of Elasticity Mercer Gauges	Moisture Content	Specific Gravity	Type of Failure
	$In.^2$	Lbs.	$Lbs/In.^2$	$Lbs/In.^2 \times 10^6$	$Lbs/In.^2 \times 10^6$	%		
			DRY COLUMN TESTS					
1	6.54	52,000	7,951	2.72	3.21	9.11	0.54	C.F.
2	6.57	52,000	7,915	3.03	4.74	8.89	0.57	C.F.
3	6.57	48,000	7,306	2.48	2.50	8.39	0.52	C.F.
4	6.59	46,000	6,980	1.92	1.71	8.52	0.50	C.G.C.F.
5	6.44	54,000	8,385	2.41	2.29	8.60	0.53	C.F.
6	6.59	52,000	7,891	2.75	2.25	7.92	0.57	C.F.
Ave.	6.55	50,666	7,738	2.55	2.78	8.57	0.53	
			WET COLUMN TESTS					
7	6.89	32,000	4,644	1.55	2.01	13.79	0.54	C.F.
8	6.93	32,000	4,618	2.54	1.69	16.42	0.55	C.F. &G.F.
9	6.80	28,000	4,118	2.21	1.51	16.68	0.54	C.F.
10	6.78	26,250	3,872	2.11	1.66	15.76	0.55	C.F.
11	6.84	32,000	4,678	1.77	2.45	14.84	0.56	C.F.
12	6.81	32,000	4,611	4.35	-	16.31	0.56	C.F.
Ave.	6.84	30,375	4,423	2.42	1.86	15.63	0.55	

C.F. - Compression failure (Crushing of the wood fibers).
C.G.C.F. - Cross-grain compression failure.
G.F. - Glue failure.

VII. DISCUSSION

1. Arch Tests

All tests indicated a marked reduction in capacity of the members at higher moisture contents. An average ultimate load capacity of 1,341 pounds was obtained for the dry arch specimens which were tested at a moisture content of 9.4%. The average ultimate load capacity of the wet arch specimens having a moisture content of 28.6% which is in the vicinity of the fiber saturation point was found to be 590 pounds. This represents approximately a 56% reduction. It is to be noted that the average values for the dry tests do not include results of specimen number 6. This specimen failed in compression as a result of cross-grain while failures in all the other dry specimens were principally tension failures beginning at scarf joints near the point of maximum moment. Serious delamination due to deterioration of the casein glue occurred in all wet specimens and, in nearly all cases, failure resulted from loss of bond strength in the glue. All failures occurred in the vicinity of the maximum moment with the exception of specimens 7 and 11. These failed by a progressive delamination beginning at the load point and continuing throughout the length of the specimens. Figure 18, the graph of ultimate load vs. moisture content for the arch specimens shows a wide scatter of points and does not indicate any definite relationship between the two quantities.

The load-strain graphs for the arch specimens are erratic for the wet specimens but show more consistency for the dry specimens. The erratic nature of the graphs for the wet specimens can probably be attributed to partial losses of bond strength in the glue at various locations causing discontinuities in the strain distribution pattern.

Load deflection relationships obtained for both wet and dry arch specimens were generally parallel to each other and, in most instances, nearly linear. For the dry specimens, ultimate deflections averaged 14.9 inches at the roller end and 7.8 inches in the vicinity of the maximum moment. In the wet specimens, an average ultimate deflection of 5.8 inches was obtained at both the roller end and at the point of maximum moment. This, however, occurred at a much lower load.

A peculiar discontinuity appeared in the graphs for most of the dry arch specimens at a load of about 1,090 pounds. This discontinuity may have been caused by a slight depression in the roller plane which may have partially impeded the roller's movement at that point. The slight depression in the roller plane may have also been responsible for a similar peculiarity that occurred in the load-strain graphs. Graphs for specimen 2 appear to exhibit more curvature than any of the others. There is a possibility that more friction was present in that test than in any of the others since specimen 2 was the first to be tested. Modifications for the purpose of reducing friction were made after that test had been completed.

The following is a comparison of test values obtained with allowable values given in the National Building Code:

a) Dry Tests

	Ultimate Test Values	N.B.C. Values	Ratio of Test Value to N.B.C. Allowable
Stress at extreme fiber in tension (Lbs./in.^{2})	6,670	2,940	2.27
Stress at extreme fiber in compression (Lbs./in.^{2})	7,120	2,940	2.42

b) Wet Tests

	Ultimate Test Values	N.B.C. Values	Ratio of Test Value to N.B.C. Allowable
Stress at extreme fiber in tension (Lbs./in.^{2})	2,910	2,350	1.24
Stress at extreme fiber in compression (Lbs./in.^{2})	3,110	2,350	1.32

From the above values it can be seen that there is a significant drop in the ratio of test value to the National Building Code allowable for the wet specimens and it appears that the allowable values in the Code may be unsafe. However, the Code actually does not permit the use of casein-type glues for cases where severe or even slight moisture conditions exist. The data obtained in these tests justifies this provision.

The fact that half of the specimens tested were "lefts" and half were "rights" appeared to have no effect on the results obtained.

2. Beam Tests

The modulus of rupture in the dry beam specimens tested at a moisture content of 9.0% was found to be 10,350 Lbs./in.^{2} while for the wet beam specimens tested at a moisture content of 18.6% a value of 7,790 Lbs./in.^{2} was obtained. This represents approximately a 25% reduction. It is to be noted that dry specimens 1 and 3 have not been included in the average values for the dry set of tests because of the low failure loads. These low values appeared to have resulted from partial damage in the bottom fibers of specimen 1 and from a scarf joint in the bottom laminate of specimen 3. The reduction in capacity was not as great as in the arch specimens because the wet beam specimens were tested at a much higher moisture content than the wet arch specimens.

Failures in both dry and wet beam specimens were principally tension failures which generally occurred in the middle third of the beam span.

Modulus of elasticity values computed by the deflection method were 2.08×10^6 Lbs./in.^{2} and 1.71×10^6 Lbs./in.^{2} for the dry and wet specimens respectively while values calculated from electrical strain gauge readings were 2.21×10^6 Lbs./in.^{2} for the dry specimens and 4.69×10^6 Lbs./in.^{2} for the wet specimens. The results of the two methods compare favourably for the dry specimens but there is considerable variation in the values for the wet specimens. It is concluded that there was an incomplete transfer of strain to the strain gauge either through loss of bond in the glue between the celluloid and the wood or between the celluloid and the strain gauge. This condition also appears in the wet column specimens where the modulus of elasticity based on electrical strain gauge readings is 1.3 times that obtained by the mechanical gauges.

Wangaard (1) states that a decrease in moisture content of one percent will increase:

a) the modulus of rupture in static bending by 4%

b) the modulus of elasticity in static bending by 2%

Applying these figures to this series of tests, the following values are predicted for the wet specimens:

a) 6,370 Lbs./in.^{2} for the modulus of rupture in static bending

b) 1.68×10^6 Lbs./in.^{2} for the modulus of elasticity in static bending as computed from deflection.

The values actually obtained in the wet tests were 7,790 Lbs./in.^{2} for the modulus of rupture and 1.71×10^6 Lbs./in.^{2} for the modulus of elasticity. This indicates very favourable agreement to predicted

values for the modulus of elasticity but poor agreement for the modulus of rupture. Why such a difference in the modulus of rupture between predicted value and actual values should occur cannot be explained.

Allowable stresses in bending at the extreme fiber as given by the National Building Code are 2,940 Lbs./in.^{2} and 2,350 Lbs./in^2 for dry and wet specimens respectively. Ultimate values obtained in these tests were 10,350 Lbs./in.^{2} for the dry specimens and 7,790 Lbs./in^2 for the wet specimens. This indicates ratios of test value to National Building Code allowable of 3.5 and 3.3 for dry and wet specimens respectively.

The load-strain graphs for the dry beam specimens are practically linear but are somewhat erratic for the wet beam tests whereas the load-deflection graphs are generally linear for both sets of tests. Figure 34, the graph of ultimate load vs. moisture content does not indicate any definite relationship between the two quantities.

3. Column Tests

The ultimate compression stress parallel to the grain in the dry specimens tested at an average moisture content of 8.6% was found to be 7,740 Lbs./in.^{2} while for the wet specimens tested at a moisture content of 15.6% a value of 4,420 Lbs./in.^{2} was obtained. This indicates a reduction from dry strength of about 43% or 6.1% per percentage increase in moisture content. This compares favourably with the value of 6% per percentage increase in moisture content as given by Wangaard (1). National Building Code values for compression parallel to the grain are 2,120 Lbs./in.^{2} for dry material and 1,550 Lbs./in.^{2} for wet material. Comparing these values to the results obtained in these tests, ratios of test values to Code values of 3.64 and 2.86 are indicated for dry and wet specimens respectively.

A comparison made on strains measured with mechanical Mercer gauges to those measured with electrical resistance strain gauges indicated agreement in some cases and disagreement in others. Differences could be attributed to several factors:

a) splitting of the wood around the screws attaching the mechanical gauge to the sample, in some instances, permitted the gauge to reverse direction in strain.

b) the mechanical gauges were tapped lightly before readings were taken. However, it was not noticed until the last few tests that appreciably different readings could be obtained by tapping the gauge at different locations.

Nevertheless, there was little difference (less than 10%) between the average values obtained for modulus of elasticity on the dry specimens by using strains measured with mechanical gauges and those measured with the electrical strain gauges.

Shrinkage of the wood in the wet specimens during the tests was assumed to be zero. Several checks made on the specimens indicated that shrinkage strains parallel to the grain were in the order of 110 micro-inches per inch per hour. An adjustment could be made for this in calculations. However, its effect would not be appreciable.

With the exception of one specimen the columns failed in compression (i.e. crushing of the wood fibers). One specimen failed as a result of a cross-grain in one of the laminations.

4. <u>Correlation of Data</u>

It is noted that the maximum tensile stress of 6,670 Lbs./in^2 calculated for the extreme fibers for the dry arch specimens is lower than either the value of 10,350 Lbs./in.^{2} obtained for the modulus of

rupture in the dry beam specimens or the value of 7,740 Lbs./in.^{2} obtained for ultimate compression stress parallel to the grain in the dry beam tests. This appears to be contradictory to the accepted idea that in members where combined beam and column action exists the ultimate strength will be intermediate between the ultimate compressive strength of the wood and its modulus of rupture. However, initial stresses produced in arch specimens by bending of the laminates during fabrication have not been taken into account in these tests. Consequently the calculated stresses for the arch are lower than what probably occurred in the member.

Theoretical computations for these arch specimens indicated that initial bending stresses produced at the extreme fibers of the individual laminates could be as high as 3,400 Lbs./in.^{2}. These initial stresses would have the effect of appreciably altering the linear bending stress distribution across the depth of a member subjected to flexure. For example, neglecting initial stresses and assuming a linear bending stress distribution throughout the depth of the member, an arch specimen subjected to flexure equivalent to 6,900 Lbs./in.^{2} tension bending stress at the extreme fiber of the top laminate would, by proportion, having a tension bending stress of 4,600 Lbs./in.^{2} at the bottom fiber of the same laminate. Now, if initial bending stresses are considered and a value of 3,400 Lbs./in.^{2} tension and compression is assumed to exist in the top and bottom fibers of the laminate it can be seen that the tension bending stress at the extreme top fiber will be increased from 6,900 Lbs./in.^{2} to 10,300 Lbs./in.^{2} while the tension stress at the bottom fiber of the same laminate will be decreased from 4,600 Lbs./in.^{2} to 1,200 Lbs./in.^{2} tension. The stress of 10,300

Lbs./in.^{2} compares quite favourably with the modulus of rupture as determined in the beam specimens. According to results obtained by T.R.C. Wilson (4) the ultimate stresses do not appear to be affected significantly by initial bending stresses. These tests appear to indicate that initial bending stresses might affect ultimate stresses quite significantly. There appears to be no other reason why ultimate arch stresses are so much lower than either those obtained in the beam or column specimens. Results of the wet arch tests cannot be compared to the wet beam or wet column tests because of the vast differences in moisture content between these tests. However, if initial bending stresses are added to the results of the wet arch specimens the resulting ultimate bending stress falls between the modulus of rupture obtained in the beam tests and the ultimate compressive strength of the column tests.

VIII. CONCLUSIONS

1. Glued laminated members glued with a casein-type of glue are highly susceptible to delamination when exposed to humid conditions for a period of time. The reduction in capacity was as high as 50% in the tests conducted.

2. Ultimate stresses at the extreme fibers of the dry arch specimens were found to be 6,670 Lbs./in.^{2} tension and 7,120 Lbs/in^2 compression. These stresses do not include effects of initial bending stresses induced during fabrication. A comparison of the ultimate tension stress of the dry specimens to the National Building Code allowable indicated a ratio of 2.27. Values of 2,910 Lbs./in.^{2} tension and 3,110 Lbs./in.^{2} compression were obtained for the wet arch specimens.

3. The ultimate bending stresses in the dry and wet beam specimens were 10,350 Lbs./in.^{2} and 7,790 Lbs./in.^{2} respectively. The value of 10,350 Lbs./in^2 for the dry specimens is 3.5 times as great as the allowable value given in the National Building Code.

4. Dry and wet column specimens failed in compression parallel to the grain at stresses of 7,740 Lbs./in.^{2} and 4,420 Lbs./in.^{2} respectively. A comparison to the National Building Code indicates a ratio of ultimate test value to allowable code value of 3.64 for the dry specimens.

5. It appears that bending stresses induced in individual laminates of arch specimens during fabrication might have a definite effect on the ultimate strength of these specimens.

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